AD-A081 059 NAVAL POSTGRADUATE SCHOOL MONTEREY CA F/G 17/7
SATELLITE NAVIGATION IN THE U.S. COAST GUARD.(U)
SEP 79 R S HARTMAN

UNCLASSIFIED NL

1 OF 2
AD
A081059

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

SATELLITE NAVIGATION
IN THE U.S. COAST GUARD

by

Richard Sheridan Hartman, Jr

September 1979

Thesis Advisor: D. A. Stentz

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Satellite Navigation in the U.S. Coast Guard		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; September 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard Sheridan Hartman, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		12. REPORT DATE September 1979
		13. NUMBER OF PAGES 126
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

LORAN-C, OMEGA, NAVSTAR GPS, RadioNavigation, Satellite Navigation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This thesis investigates many of the issues surrounding the civil maritime navigation dilemma facing the USCG. At present, LORAN-C and OMEGA, which are hyperbolic radionavigation systems and TRANSIT, a Doppler shift satellite-based system, are the main systems employed in the civil maritime field. NAVSTAR GPS, a passive ranging satellite navigation system is, in the meantime, showing great promise as the replacement system for primary radionavigation in the U.S. There are several key questions, one involving national

security, which must be answered, however, before NAVSTAR becomes operational. What positional accuracy will be made available to the civil community? What are the economics of the user equipments? Will NAVSTAR be accepted as a successful replacement for LORAN by the civil community? To aid in answering some of these questions, the results of an informal survey of the civil maritime industry are presented. The final outcome remains to be seen. These issues will require careful thought by this country's top leaders before any final committment to NAVSTAR can be made or prior to any decision to discontinue LORAN-C or OMEGA.

Approved for public release; distribution unlimited.

SATELLITE NAVIGATION IN THE U.S. COAST GUARD

by

Richard Sheridan Hartman, Jr.
Lieutenant, United States Coast Guard
B.S., United States Coast Guard Academy, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN TELECOMMUNICATIONS
SYSTEMS MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 1979

Author: Richard Sheridan Hartman Jr.

Approved by: ______ Thesis Advisor

______ Second Reader

______ Chairman, Department of Administrative Sciences

______ Dean of Information and Policy Sciences

ABSTRACT

This thesis investigates many of the issues surrounding the civil maritime navigation dilemma facing the USCG. At present, LORAN-C and OMEGA, which are hyperbolic radionavigation systems and TRANSIT, a Doppler shift satellite-based system, are the main systems employed in the civil maritime field. NAVSTAR GPS, a passive ranging satellite navigation system is, in the meantime, showing great promise as the replacement system for primary radionavigation in the U.S. There are several key questions, one involving national security, which must be answered, however, before NAVSTAR becomes operational. What positional accuracy will be made available to the civil community? What are the economics of the user equipments? Will NAVSTAR be accepted as a successful replacement for LORAN by the civil community? To aid in answering some of these questions, the results of an informal survey of the civil maritime industry are presented. The final outcome remains to be seen. These issues will require careful thought by this country's top leaders before any final committment to NAVSTAR can be made or prior to any decision to discontinue LORAN-C or OMEGA.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

APL	Applied Physics Laboratory
C/A	Course Acquisition
CCZ	Coastal Confluence Zone
CFR	Code of Federal Regulations
CO	Commanding Officer
CRT	Cathode Ray Tube
CW	Continuous Wave
CYCLAN	Cycle Matching LORAN
DOC	Department of Commerce
DOD	Department of Defense
DOT	Department of Transportation
DR	Dead Reckoning
DSARC	Defense Systems Acquisition Review Council
FAA	Federal Aviation Administration
GAO	Government Accounting Office
GRI	Group Repetition Interval
GCS	Ground Control Station
HF	High Frequency
HHE	Harbor and Harbor Entrance
kHz	Kilohertz
kW	Kilowatt
LF	Low Frequency
LOP	Line of Position
LORAN	Long Range Aid To Navigation
LRE	LORAN Replacement Equipment
MARAD	Maritime Administration

MCS	Master Control Station
MF	Medium Frequency
MHz	Megahertz
MS	Monitor Station
NASA	National Aeronautics and Space Administration
NAVSAT	Navy Navigation Satellite System
NAVSTAR GPS	Navigation System Using Timing and Ranging Global Positioning System
NGFS	Naval Gunfire Control System
NM	Nautical Mile
NPN	National Plan For Navigation
NRL	Naval Research Laboratory
NTS	Navigation Technology Satellite
OOD	Officer of the Deck
P	Precision
RFI	Radio Frequency Interference
SAMSO	Space and Missile System Organization
SATNAV	Satellite Navigation
STS	Space Transportation System
TIMATION	Time Navigation
UCT	Universal Coordinated Time
USC	United States Code
USCG	United States Coast Guard
VHF	Very High Frequency
VLF	Very Low Frequency

I. OVERVIEW OF NAVIGATION

A. INTRODUCTION

The U. S. Coast Guard (USCG) has been tasked through federal regulations to provide an aids to navigation (ATON) system adequate to serve the needs of both the Armed Forces and the commerce of the United States. This system refers to such varied devices as buoys, lighthouses, dayboards, radiobeacons and LORAN. For the purposes of this thesis, aids to navigation will focus on electronic aids, specifically LORAN-C, OMEGA and satellite navigation in its several evolutionary stages. To further narrow the scope of this discussion, consideration of system users other than those in civil maritime segment will be kept to a minimum.

It is the intent of this presentation to examine the existing navigation systems for civil maritime users (assumed to be a working mix of LORAN-C and OMEGA and the prime candidate to replace present systems, namely NAVSTAR Global Positioning System (GPS), the latest evolution in the satellite navigation life process. This examination is felt to be important due to the contention by the General Accounting Office (GAO) that there is far too much overlap and proliferation of aids to navigation systems; and that this redundancy imposes unnecessary costs to the American taxpayer.[1] GAO has, therefore, proposed a significant reduction in existing and planned

[1] Reference 1, p. i.

systems and has recommended a national manager to oversee the effective and efficient utilization of navigation systems. Figure 1-1 lists the thirteen navigation systems, as identified by GAO, in which "considerable navigation overlap exists because by their contention the navigation needs of most user communities could be satisfied, equally or better, by one or more systems other than the system primarily used".[2] Of these, the U.S. Coast Guard operates four - non-directional radio beacons, LORAN-A (phasing out), LORAN-C, and two OMEGA stations.[3]

33 CFR (Code of Federal Regulations) will provide the limits of investigation of this article. It states that any aids "to be established, maintained and operated by the Coast Guard to serve the needs of commerce must be necessary for the safety of navigation, useful for commerce of a substantial and permanent character, and must be justified in terms of public benefit to be derived therefrom".[4] Thus the question becomes the following: how can civil maritime users be provided reliable, accurate and cost-effective navigation aids in the face of cost cuts and reduced overlap dictated by GAO? With the advent of NAVSTAR, satellite navigation presents system users, as well as operators, with the dilemma of whether or not to continue with LORAN and OMEGA, or shift to

---

[2] Ibid., p. 10.

[3] Authority for operating these comes from 14 USC 81.

[4] Reference 2, p. 222.

Navigation System	Cost (M)	Operator(s)
Non Directional Rad Beacons	$ 17.8	FAA, USCG, DoD
VOR	41.4	FAA, DoD
TACAN	142.5	FAA, DoD
LORAN-A[1]		USCG
LORAN-C	24.0	USCG
LORAN-D	15.3	USAF
OMEGA	21.4	USCG
TRANSIT	5.5	USN
INERTIAL	438.2	N/A
DOPPLER RADAR	123.8	N/A
DIFFERENTIAL OMEGA[2]		
PLRS	39.2	USA, USMC
NAVSTAR	2,895.0	DoD, CIVIL(?)
TOTAL	$3,764.1	

[1] being phased out
[2] recently terminated

* This list conflicts to some extend with NPN (National Plan for Navigation), which recognizes the following:

Operating Systems	Developmental Systems
1. LORAN A	1. Microwave Landing Systems
2. LORAN C	2. NAVSTAR GPS
3. OMEGA	
4. VOR/TACAN	
5. Radio Beacons	
6. ILS	

Figure 1-1 List of Navigation Systems*
(Source: Reference 8, p. 3-2)

satellite navigation (contingent upon such factors as receiver cost, civil user availability, and system reliability) at the expense of the present navigation systems; or to utilize some mix of the two systems, or perhaps follow some other alternative.

B. A HISTORY OF NAVIGATION

Bowditch defines navigation as "the process of directing the movements of a craft from one point to another".[5] This process should be viewed as an art, considering the evolution of marine navigation. Piloting was likely the earliest form of navigation. As man ventured tentatively onto the waters near his homeland, familiar landmarks were used as reference points to guide the novice sailor back to his port of departure. As he gained confidence to venture further from shore the need for predicting future positions arose. Therefore, dead reckoning (DR) was likely the next step in this evolutionary process. Then as man gathered more information and confidence about the movements of heavenly bodies, celestial navigation using the position of the sun, moon, planets and stars in relation to the earth came to be commonly used. There is evidence then that "steering" by the heavens had been taking place since the earliest days of navigation. Finally, with the advent of modern technology, electronic navigation has come to the forefront of techniques used to guide man's vessels from one port to the next.

---

[5] Reference 3, p. 15.

Some archaeologists believe that the art of navigation originated nearly 8000 years ago in the eastern Mediterranean.[6] A written sailing direction is known to have existed several hundred years before Christ - the Periplus of Scylax - and may have included a prototype form of chart.[7] This record contained information on distances to different ports and provided details on the various dangers which lurked nearby and navigational aids which existed. It also provided data on port facilities; its contents were very similar to the contemporary sailing directions well known to modern mariners. A book of observations written by one Pytheas of Nassaiia (Greek astronomer and navigator) provides a detailed account of one of the earlies recorded voyages made by man.[8] Sometime in the latter half of the fourth century B.C. he sailed an established trade route from the Mediterranean to England, then on to Scotland, the fiords of Norway and rivers in the north of Germany. The significance of this and other voyages of the time is that no compasses, chronometers, electronic aids or sextants were yet in existence. Yet these hardy mariners had enough working knowledge of the sun, wind and stars to be able to fix their positions sufficiently well to set out and then return home.

Advances in the navigation art came about slowly during the early centuries after Christ, all but stopping during the

---

[6] Reference 4, p. 4

[7] Ibid.

[8] Reference 4, p. 16.

the Dark Ages then spurting forward with the dawn of Europe's golden age of discovery. Works comparable to Pytheas's observations (written in book form like Ports Around the World) did not appear for some 1500 years after his time, but when they did appear they were in the form of "portolanos", or sailing directions, for the Mediterranean, which included, surprisingly, very accurate charts.[9] Next came the "routiers" of France (called rutters by the British) and the Mariner's Mirror, a very good Dutch text by Waghenaer. In 1557 the Brieve Compendio del Arte del Navigar appeared in Italy.[10] It was intended to be a general treatise on navigation, and not just a set of sailing directions.

The evolution of navigational equipments is of extreme importance in understanding the art of navigation. The first worthwhile device was the magnetic compass, which in its earliest form was a small needle magnetized using a lodestone and set on the surface of a small container of water by means of a float. Its origins are unknown; however the Vikings may have used such a contrivance in the eleventh century.[11] The next instrument to make an appearance was the cross-staff. It was the first device able to successfully measure the altitude of celestial bodies. Its use was difficult and quite a feat to master; yet it enabled a practiced navigator to obtain the altitude of a heavenly object, at sea, with an

---

[9] Reference 4, p. 5.

[10] Ibid.

[11] Ibid.

accuracy of almost one degree. In 1590, John Davis introduced the backstaff.[12] This device was based upon the concept of the cross-staff, but was far more easy to use. Future models permitted measurements of other bodies besides the sun. Aother device which proved invaluable was the chip log. This log, towed astern of the vessel, permitted the navigator to compute his speed. Counting the number of knots in the log's line against a known period of time yielded a rough approximation of the vessel's speed. This knot counting is probably the origin of the term "knot", which today means one nautical mile per hour.

Accurate navigation was not possible until the invention of the chronometer and sextant in the early 1700's. The chronometer was important because its precise timekeeping properties permitted the navigator to determine his longitude afloat. The first chronometer accurate enough for shipboard use is credited to John Harrison of Yorkshire, England.[13] During the period 1735 to 1761 he constructed four very accurate chronometers, with errors of less than two minutes of longitude (or less than eight seconds slow) on round trips from England to the Carribean and back. Pierre Le Roy, a Frenchman, devised a chronometer model, in 1766, which provided the basis of all such instruments built since then.[14] The sextant is attributed to two men - John Hadley of England

---

[12] Ibid., p. 6.

[13] Reference 3, p. 46.

[14] Ibid., p. 47.

and Thomas Godfrey of Philadelphia - who arrived independently at its design in 1730.[15] Its importance lies in the ease with which altitudes could be measured, not only of the sun but also the moon, planets and stars.

The twentieth century has proven no less a contributor to the revolutionizing of the art of navigation. Iron ships required a compass which would always indicate true north, despite the interference and disturbance of the magnetic hull. Working independently, Elmer Sperry of the U.S. and Anschutz-Kampfe of Germany, developed the gyro compass in the early 1900's. Sperry's device was proven adequate in 1911;[16] and since then has become standard equipment on naval and merchant vessels alike. Depth finders, radio direction finders, radar and various electronic aids to navigation (such as LORAN, OMEGA, and SATNAV) have all come into being in the last half century and play essential roles in the safe transit of vessels.

C. THE EVOLUTION OF AIDS TO NAVIGATION

The earliest lighthouses known were towers, constructed along the Mediterranean coast of Egypt, in which beacon fires were fueled by priests.[17] The Pharos of Alexandria, one of the seven wonders of the ancient world, was a lighthouse which may have risen more than two hundred feet in the air. The earliest known wave-swept lighthouse, the light of

---

[15] Reference 4, p. 7.

[16] Reference 3, p. 24.

[17] Ibid., p. 28.

Courdouan, was erected at the entrance to the Gironde river in western France sometime between 1584 and 1611.[18] In England lighthouses were privately maintained by organizations interested in navigation. One famous group, Trinity House, had its origins in the 16th century: its purpose was to design, construct and establish beacons, marks and signs and to make pilots available to ships.[19] The first lightship was a small craft with lanterns hanging from the yardarms. It was positioned on an estuary of the Thames in London in 1732.[20]

In the Colonies prior to the War of Independence, aids to navigation were the responsibility of local or colonial governments, England having exhibited a great degree of indifference toward the responsibility of making the waters safe for mariners. The first lighthouse in America was the Boston Lighthouse located on Little Brewster Island in Boston Harbor. It was first exhibited on September 14, 1716.[21] The first mention of buoys in the American colonies occurred in the building records of Cape Henlopen Lighthouse by Pennsylvania, which describe two sets of buoys in the Delaware River at a cost of 1143 pounds.[22] These were probably logs or kegs.[23]

---

[18] Ibid.

[19] Ibid.

[20] Ibid.

[21] Reference 5, p. 4.

[22] Reference 6, p. 214.

[23] Reference 4, p. 67.

In 1789 the forerunner of the U.S. Coast Guard, the Revenue Marine, was established at the urging of Alexander Hamilton, who saw the need of a floating force to collect tariffs and halt smuggling. In this same year the Congress passed a law which created the Lighthouse Establishement.[24] Its purpose was to provide "the necessary support, maintenance, and repairs of all lighthouses, beacons, buoys and public piers erected...for rendering the navigation thereof easy and safe.."[25]

During the period from 1789 to 1842, lighthouse construction, supply and inspection was performed by contract, while administration of all aids was carried out by the Treasury Department.[26] In 1820 the first U.S. lightship was stationed in Chesapeake Bay, at the entrance to the Elizabeth River near Norfolk.[27] In 1850 Congress provided for a systematic coloring and numbering scheme for all buoys.[28] In 1915 the Revenue Cutter Service and the Life-Saving Service were combined to form the U.S. Coast Guard. Subsequently in 1939, under Presidential Reorganization Plan Number 11 the Bureau of Lighthouses was transferred to the Coast Guard along with all the aids, authority for marine aids to navigation as well as all other functions.[29] A discussion of the efforts to

---

[24] Reference 5, p. 5.

[25] Reference 7, p. 2.

[26] Reference 5, p. 6.

[27] Ibid.

[28] Ibid., p. 12.

[29] Ibid., p. 39.

develop an electronic navigation system (LORAN) during World War II is given in Chapter II; no further mention is made in this section.

Today the U.S. Coast Guard is tasked with the maintenance and operation of all lighthouses and other aids along nearly 40,000 miles of coastline in the U.S. and its territories. This includes over 13,000 lighthouses and minor lights as well as some 22,000 lighted and unlighted buoys.[30] Radio beacon stations, LORAN and OMEGA stations account for another sizable area of navigation responsibility shouldered by the Coast Guard. In the following section a brief survey of the legislation covering the operation of these aids will be presented.

D. AIDS TO NAVIGATION LEGISLATION

The Department of Transportation (DOT) is the primary provider of civil aids to navigation (as well as certain systems used by the military)-[31] the two major agencies within DOT that provide these services being the Federal Aviation Administration (FAA) and the U.S. Coast Guard. Public Law 89-670, also known as the Department of Transportation Act, tasks the Secretary of Transportation with full responsibility for navigation matters within DOT and further directs the Secretary to promulgate the National Plan for Navigation, which is the source of U.S. government policy and plans for navigation systems of interest to and used by the

---

[30] Reference 4, p. 67.

[31] Reference 8, p. 1-2.

the civil community.[32] Within DOT are several agencies with certain statutory responsbilities for satisfying U.S. navigational requirements. The FAA is charged by Public Law 85-276 (the Federal Aviation Act of 1958) with the responsibility of developing and implementing radionavigation systems that meet the needs for safe and efficient navigation and control of all civil aviation and much of military aviation (except those needs peculiar to air warfare or of concern primarily to military agencies only).[33]

The U.S. Coast Guard is mandated to define the need for and to provide aids and facilities required to assure safe and efficient maritime navigation. Section 81 of Title 14 United States Code states:

> "In to aid navigation and to prevent disasters, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain and operate: (1) aids to maritime navigation required to serve the needs of the armed forces or of the commerce of the United States; (2) aids to air navigation required to serve the needs of the armed forces of the United States peculiar to warfare....; and (3) electronic aids to navigation systems-(a) required to serve the needs of the armed forces of the United States peculiar to warfare....; or (b) required to serve the needs of the maritime commerce of the United States; or (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Agency. These aids to navigation other than electronic aids to navigation systems shall be established and operated only within the United States, the waters above the Continental Shelf, the territories and possessions of the United States, the Trust Territory of the Pacific Islands, and beyond the territorial jurisdiction of the United States at places where naval or military bases of the United States are or may be located."[34]

---

[32] Ibid., p. xi.

[33] Ibid., p. 1-3.

[34] Ibid.

In addition more specific provisions governing Coast Guard activities in the field of navigation are contained in Title 33 Code of Federal Regulations (parts 1-199), revised 1 July 1978. Part 62 of 33CFR is entitled United States Aids to Navigation System and contains several subparts which are germane to the issue under investigation in this paper. Subparts 62.01-5 and 62.01-10 permit the Coast Guard to establish, maintain and operate aids to navigation to meet the needs of the Armed Forces and Federal Agencies other than the Armed Forces, respectively. Additionally, Subpart 62.35 enumerates the details of maritime radiobeacons. Finally, Subpart 62.40 covers the subjects of LORAN-A and LORAN-C including a basic system description, rate designations and cautionary notes about improper matching of signals.

In chapters 2 and 3, the emphasis of the presentation will shift to systems - background, description and operation. Chapter II will deal with LORAN/OMEGA in the context that these two systems are the presently utilized civil maritime navigation system mix (this supposition is upheld by the National Plan for Navigation[35]). Chapter III will describe NAVSTAR GPS, in its proposed operational framework and with some comparisons to the present civil aid to navigation program. Chapter IV will further analyze the comparison between present and proposed navigation plans, with emphasis on errors, costs and other constraints. Finally, Chapter V

35 Ibid., p. D-2.

will present the results of a non-statistical survey of the civil marine industry and its feelings towards LORAN, SATNAV and the legislative efforts surrounding various plans to make one or the other (or both) the primary navigation system(s) for the United States.

II LORAN-C AND OMEGA

A. INTRODUCTION TO LORAN

LORAN is an acronym derived from the expression LOng RAnge Navigation: it defines an electronic navigation system that employs pulsed radio emissions and which measures the time differences between the reception of various pulses from widely separated transmitting stations. Navigational fix data is in the form of hyperbolic lines of position. The theory of such hyperbolic aids rests on the principle that the difference in time of arrival of radio signals from two stations, observed at some point within the coverage area, is a measure of the difference in distance from the point of observation to each of the stations (Figure 2-1 describes this geometry). The locus of points having the same observed difference in distance to a pair of stations is a hyperbolic line of position (LOP): the intersection of two or more LOP's defines a fix.

B. HISTORY OF LORAN

The first known use of a hyperbolic system to locate some position was during World War I; time measurements of arriving sound waves at three different listening posts were taken and the location of some hidden cannon was then determined.[36] The possibility of using a pulsed radio navigation system had

---

[36] Reference 9, p. 5.

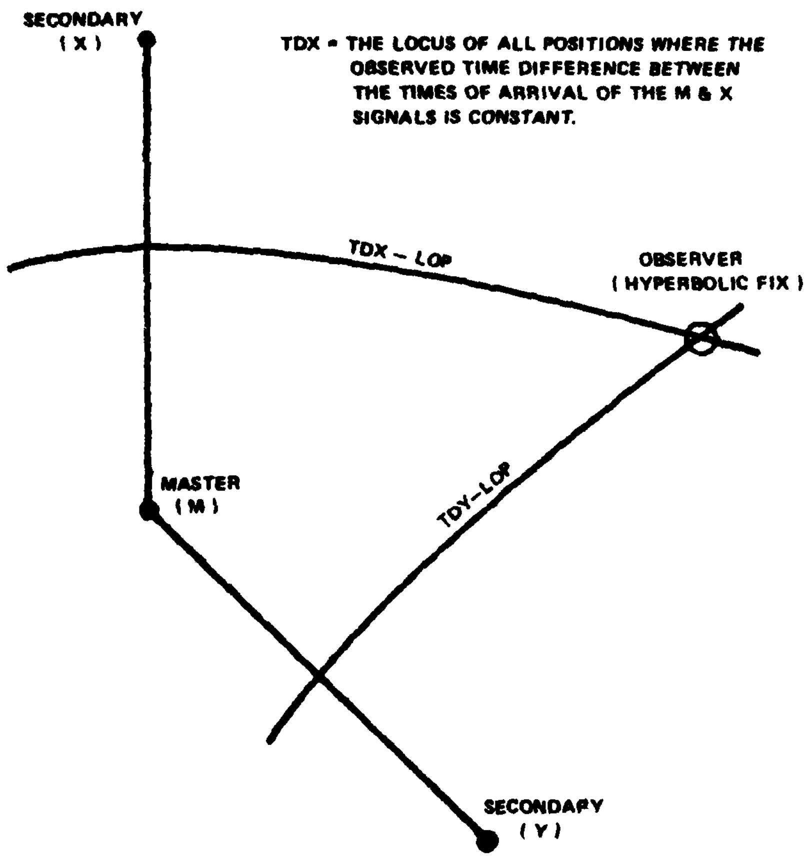


Figure 2-1 Hyperbolic Fix Geometry

(Source: Reference 12, p. 3)

simultaneous origins in both Great Britain and the United States. Alfred L. Loomis of the Microwave Committee-representatives of MIT, government and industry-formally proposed such a system in October 1940; Robert J. Digby of England foresaw such a system and directed its development (this British system was known as "Gee").[37] By early 1941 a development group headed by Melville Eastham at MIT's Radiation Laboratory had been established and was pursuing the system concepts which later became known as LORAN. From the summer of 1942 on the two groups closely coordinated their efforts; successful application of the principles of hyperbolic measurement rested on two factors - 1) development of radio frequency generators capable of producing peak power outputs in the hundreds of kilowatts (KW), and 2) development of equipment which permitted relative time measurements to an accuracy of one millionth of a second.[38] Once these needs were met, hyperbolic radionavigation systems-urgently needed as all-weather navigation aids for wartime operational missions-became technically feasible.

The first practical hyperbolic system, Gee, was in operation by 1942, and was extensively used by high-flying bombers of the allied Air Forces during World War II. This system employed transmitted radio pulses of 2-10 microseconds duration synchronized from three or four transmitting stations separated by approximately 75 miles. Differences in times of arrival

---

[37] Ibid.

[38] Reference 10, p. 5.

of the pulses from the various ground stations were measured using a cathode ray (CRT) oscilloscope incorporated into a special receiver indicator unit (the CRT permitted measurement accuracies on the order of one microsecond or better). The time base of reference was generated by a highly stable oscillator. Accuracies of 2-3 miles were standard, while at the maximum system range of approximately 300 miles, five mile errors were more likely.[39]

The development of LORAN in the United States stemmed from a set of specifications called for by the National Defense Research Committee; these included a system with an accuracy of 1000 feet at 200 miles. The solution to this was the use of synchronized pairs of pulse type transmitting stations, separated by several hundreds of miles and radiating up to 1.5 million watts.[40] The original concept also called for the use of groundwave signals only; however it was discovered that pulses could be reflected off the ionosphere and retain their timing stability. Combining this skywave phenomenon with groundwaves, a fix accuracy of 5 miles at a range of 1500 miles could be readily obtained.[41] Because this accuracy was much more than anticipated in the original ground wave only concept, all research efforts were directed to this groundwave-skywave combination. By June 1942, first generation peak pulse power transmitters had been developed and

---

[39] Ibid., p. 6.

[40] Ibid.

[41] Ibid., p. 7.

installed at experimental stations on the Coast Guard facilities at Montauk Point, Long Island, New York and Fenwick Island, Delaware.[42]

In early 1942 skywave accuracy tests were conducted: the results were so encouraging that a four-station chain was established for field trials. By spring 1943 the first Standard LORAN System became operational. It consisted of the initial two test stations, plus two more at Baccaro and Deming, Nova Scotia. The Fenwick station was later moved to Cape Hatteras, North Carolina while the site at Montauk was relocated to Nantucket Island, Massachusetts. This first version operated in the 1800-2000 kilohertz band and formed the basis of what is now known as LORAN-A. In addition to Standard LORAN there were several variations undergoing evaluation. The most successful was known as Skywave Synchronized (SS) LORAN.[43] As the name implies SS LORAN maintained synchronization using skywaves rather than groundwaves. This system was so successful that by late 1944 nighttime bombing missions over virtually all of Europe with accuracies of 1-2 miles, were possible. The one drawback was the lack of daytime coverage.

During the early stages of the program it was well known that a low frequency LORAN system would be more accurate and have greater navigational ranges, during both day and night, with fewer transmitter sites. As a result the first experimental low frequency LORAN (LF LORAN) system was in operation

---

[42] Reference 9, p. 5.

[43] Reference 10, p. 8.

in 1945. Similar to Standard LORAN in technique, LF LORAN operated at 180 kHz. Further tests revealed an accuracy on the order of 160 feet at 750 miles (beyond this range accuracy dropped due to skywave interference).[44] Coverage was possible over land (about 2/3 effectiveness compared to over-water coverage) as well, and operation of the system included full 24-hour availability. The system was unacceptable for general navigation however due to ambiguities in positions resulting from cycle matching errors (the system operated by visually matching pulses and cycles of the transmitted signal). Efforts by joint government and industry teams resulted in a new low frequency, cycle-matching system called CYCLAN (CYCLe matching LORAN).

CYCLAN was the first fully automatic LORAN system. The cycle-matching problem of LF LORAN was resolved by using pulse transmissions on two frequencies 20 kHz apart. System coverage was limited to the groundwave region and operational ranges were about 1000-1500 miles. Testing was difficult due to interference from broadcast stations and aeronautical beacons on adjacent frequencies (CYCLAN operated at 160 and 180 kHz).[45] The situation was further complicated as a result of the 1947 Atlantic City Radio Conference, which designated the 90-110 kHz band (with 20 kHz bandwidth) for long range navigational systems (CYCLAN was in the 160-180 kHz range with 40 kHz bandwidth). However, the system did prove the

---

[44] Ibid., p. 11.

[45] Ibid.

feasibility of cycle-matching and much work in instrumentation was also completed.

The origin of LORAN-C dates back to 1952 when work began on a long range, automatic, ground-reference tactical bombing system known as CYTAC. Integral to CYCTAC was a pulsed, hyperbolic navigation system in 90-110 kHz band. Three stations were built in New York, North Carolina and Florida: the coverage area included that portion of the U.S. east of the Mississippi, with excellent accuracy. The system concept was abandoned due to operational reasons; however its value as a navigation aid was instantly recognized. In 1957 an operational requirement for a highly accurate long range maritime radio navigation aid came into being.[46] LORAN-A could not meet the specifications; it was felt that the CYCTAC concept and some of its equipment would be more than adequate. As a result the first chain of this new system-eventually designated as LORAN-C - was placed into operation in 1957. Its three stations were located at Martha's Vineyard, Massachusetts, Carolina Beach, North Carolina, and Jupiter, Florida. The Coast Guard assumed operational responsibility for the system in August, 1958.[47]

The LORAN-C system has been in constant expansion since its inception. The Mediterranean chain was constructed in 1959, and was followed by the Norwegian Sea chain in 1960.

---

[46] Ibid., p. 14.

[47] Reference 11, p. 2-1

In 1961 the Northern Pacific and Central Pacific chains were completed; in 1964 the Northwest Pacific chain went "on-air". The Southeast Asia chain commenced operation in 1966 (and terminated at the end of hostilities in VietNam). The LORAN 70's program (an expansion and upgrading effort) is nearing completion and will provide coverage of the Coastal Confluence Zone (CCZ)[48] of the continental U.S. These chains will include the Gulf of Alaska, Canadian West Coast, West Coast, Gulf of Mexico, Great Lakes, Northeast U.S., Southeast U.S. and expanded North Atlantic. Total coverage will approach 16 million square miles (Figure 2-2 depicts the station locations). As this is a transition period from LORAN-A to total LORAN-C, LORAN-A will be continued for some period of time to permit users to obtain new receivers and provide for continual coverage in the meantime (Figure 2-3 provides an approximate picture of coverage areas of LORAN-C).

C. THE LORAN-C SYSTEM

LORAN-C is a pulsed, low-frequency hyperbolic radioavigation system. Its high degree of accuracy stems from time difference measurements of the pulsed carrier. The system operates on the notion that differences in arrival times of radio signals from two widely separated transmitters, observed at a location within the area of coverage, are measures of the difference in distance from the point of observation to each

[48] CCZ-defined as that area of water extending from the shore outward for 50 nautical miles or to the 100 fathom line, whichever is farthest from shore. It's the area where transoceanic traffic converges and where interport traffic exists.

Chain	Station		Peak Power (MW)	Ant Ht (M)
Northwest Pacific........	Iwo Jima Is.	(M)	1.8	411.5
	Marcus Is.	(W)	"	"
	Hokkaido, Jp.	(X)	.4	190.5
	Geshashi, Ok.	(Y)	"	"
	Yap Is.	(Z)	1.5	304.8
Central Pacific..........	Johnston Is.	(M)	.3	190.5
	Upolu Pt., HI	(X)	"	"
	Kure Is.	(Y)	"	"
North Pacific............	St. Paul Is. AK	(M)	"	"
	Attu Is., AK	(X)	"	"
	Port Clarence, AK	(Y)	1.0	411.5
	Narrow Cape, AK	(Z)	.4	190.5
Gulf of Alaska...........	Tok, AK	(M)	.4	SLT*
	Narrow Cape, AK	(X)	see above	
	Shoal Cove, AK	(Y)	.4	SLT

*SLT-sectionalized tip antenna; consists of four 125' towers arranged as vertices of a square.

Chain	Station		Peak Power (MW)	Ant Ht (M)
Canadian West Coast......	Williams Lake, CD	(M)	.4	190.5
	Port Hardy, CD	(X)		
	Shoal Cove, AK	(Y)	see above	
	George, WA	(Z)	1.2	SLT
West Coast U.S...........	Fallon, NE	(M)	.4	190.5
	Searchlight, NE	(X)	.5	SLT
	Middletown, CA	(Y)	.4	190.5
	George, WA	(Z)	see above	
Great Lakes..............	Dana, IN	(M)	.35	"
	Seneca, NY	(X)	.8	213.5
	Baudette, MN	(Y)		"
	Malone, FL	(Z)	.35	190.5
Northeast U.S............	Seneca, NY	(M)	see above	
	Dana, IN	(W)	"	
	Carolina Beach, NC	(X)	.7	150
	Caribou, Maine	(Y)	developmental	
	Nantuckett, MA	(Z)	.3	190.5
Southeast U.S............	Malone, FL	(M)	.8	213.5
	Grangeville, LA	(W)	"	"
	Raymond, TX	(X)	.4	"
	Jupiter, FL	(Y)	.3	190.5
	Carolina Beach	(Z)	see above	
North Atlantic...........	Angissoq, Greenland	(M)	1.0	190.5
	Sandur, Iceland	(X)	1.8	411.5
	Ejde, Faeroe IS	(Y)	.4	190.5
	Cape Race, New Foundland	(Z)	1.8	411.5

(all above stations host nation manned)

Norwegian Sea............	**Ejde, Faeroe Is.**	**(M)**	**see above**	
	BO, Norway	**(X)**	**.2**	**190.5**
	Sandur, Iceland	**(Y)**	**see above**	
	Jan Mayen, Norway	**(Z)**	**.2**	**190.5**
	Sylt, Germany	**(W)**	**.3**	**"**
	(Sylt only U.S. manned station)			
Mediterranean Sea........	**Simeri Crichi, Italy**	**(M)**	**.2**	**190.5**
	Lampedusa, Italy	**(X)**	**.4**	**"**
	Kargarburun, Turkey	**(Y)**	**.2**	**"**
	Estartit, Spain	**(Z)**	**"**	**"**
	(Kargarburun not transmitting at present)			

NOTE: **M designates the Master Station**
W, X, Y, Z designates the Secondaries

Figure 2-2 LORAN-C Chain Configuration

(Source: LCDR William Schorr, USCG
(G-EEE)
USCG Headquarters
Washington, D.C.)

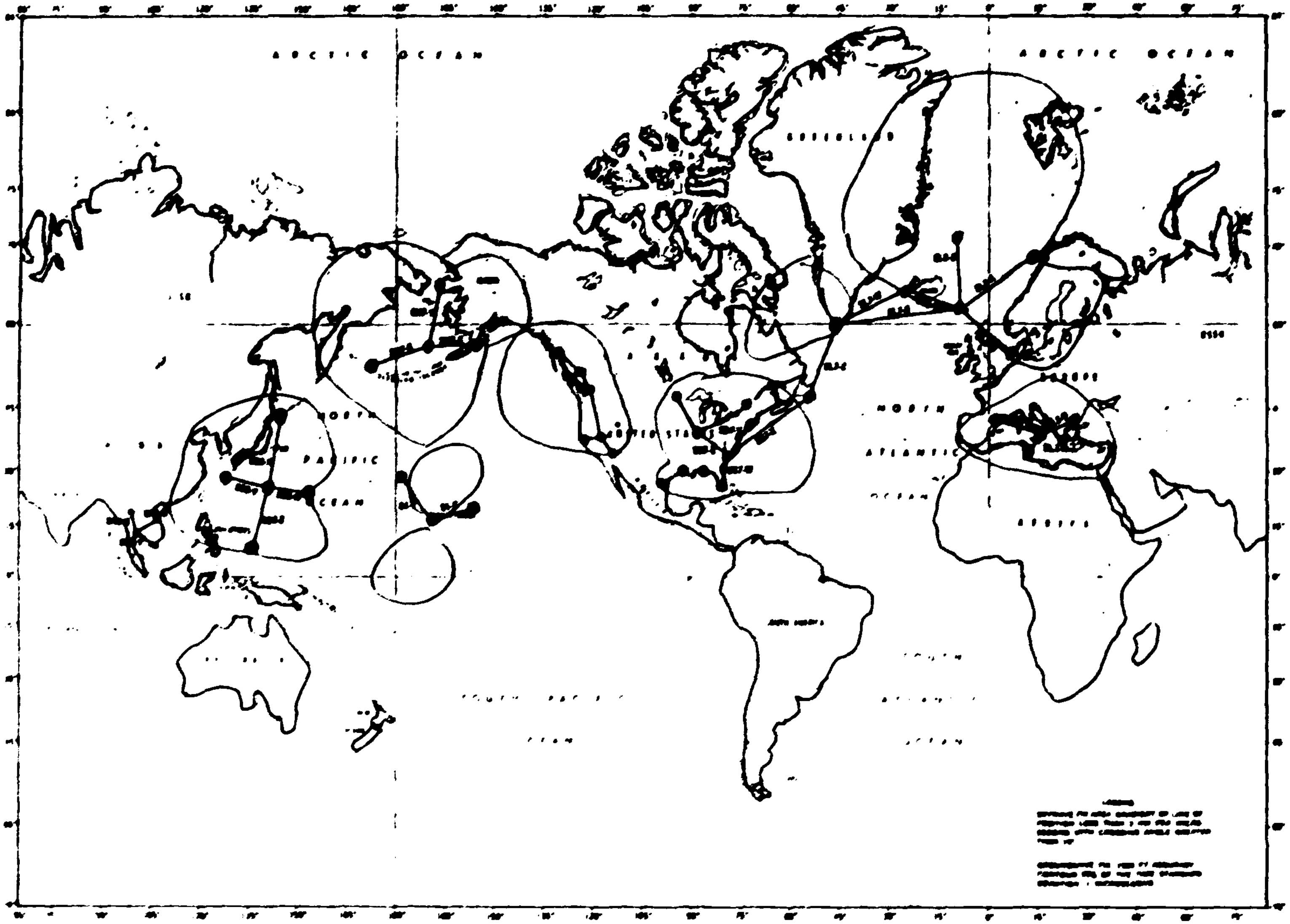


Figure 2-3 LORAN-C World Coverage
(Source: Reference 11, p. 2-3)

of the transmitter sites.[49] The locus of points with the same observed difference in distance to a pair of two stations is a hyperbolic line of position (LOP), and the intersection of two or more LOP's defines a fix. Low frequency (100 kHz center frequency) was chosen for LORAN-C for several reasons, two of which were stable propagation characteristics and long range capability. Very low frequency (VLF) was inadequate due to lack of real-time knowledge of ionospheric conditions. Medium frequency (MF) and high frequency (HF) suffer high propagation losses over land, and very high frequency (VHF and above) is limited to line of sight. In selecting a radionavigation system frequency, factors to be considered include widest area of coverage with a high degree of accuracy. The basic limiting factor for accuracy is the velocity of radio energy propagation. This velocity is nearly one foot per nanosecond. However this is under ideal, "free-space" conditions, in a vacuum with no interfering factors. Of course these ideal conditions do not exist on earth. The land and the earth's ionosphere affect the velocity of radiowave propagation, thereby reducing it. These affects are measurable however and can be accounted for in the numerical computations. To obtain accuracies with errors on the order of tens of hundreds of feet, measurements must be made to the tens or hundreds of nanoseconds-to accomplish this then, very accurate timing devices must be incorporated into the system.

---

[49] Reference 12, p. 2.

[50] Reference 11, p. 2-4.

The LORAN-C signal format consists of pulsed and coded signals used to minimize skywave effects (skywaves are echoes of the transmitted pulses reflected from the ionosphere). Skywave problems include an arrival at the receiver of as little as 35 microseconds after arrival of the groundwave, or as much as 1000 microseconds after the groundwave.[51] In either case distortion of the signal is caused by overlapping of pulses. This difficulty has been overcome in LORAN-C by (1) the shape of the fast-rising LORAN-C pulse which allows for accurate time of arrival measurements on the first part of the pulse (see Figure 2-4), and which offsets the early arriving skywave problem; and (2) the phase of the 100 kHz carrier which is changed 180° in each pulse in accordance with a preset pattern called the Phase Code (see Figure 2-5).[52] The LORAN-C system is such that ranges of 800-1200 nautical miles (NM) are typical with position variations of 50-200 feet at 500 NM and 500 feet at 1000 NM.[53]

LORAN-C chains are comprised of a master station, two or more secondary stations (also called slaves) and various system area monitor (SAM) stations. Master and slaves are generally configured in a "Wye", Triad or Star arrangement. The transmitting stations are fixed so that signals from at least the master plus two slaves can be received throughout

---

[51] Ibid., p. 2-5.

[52] Ibid.

[53] Reference 12, p. 4

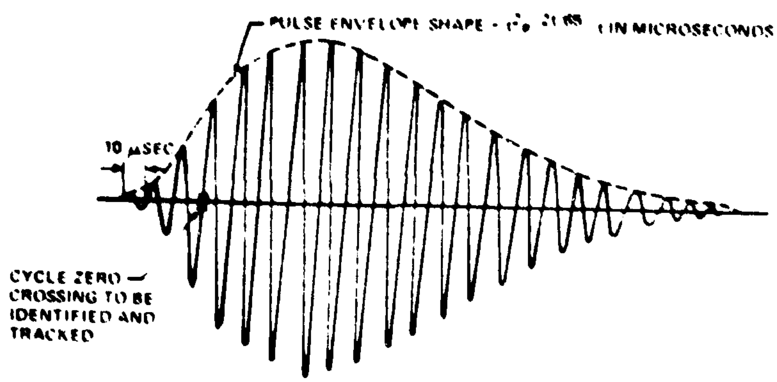


Figure 2-4 LORAN-C Pulse

(Source: Reference 12, p. 5)

	MASTER	EACH SECONDARY
GRI A	++−−+−+− +	+++++−−+
GRI B	+−−+++++ −	+−+−++−−

NOTE: (+) INDICATES ZERO DEGREE CARRIER PHASE
(−) INDICATES 180° CARRIER PHASE
LORAN–C INTERVALS A&B ALTERNATE IN TIME

Figure 2-5 LORAN-C Phase Codes

(Source: Reference 12, p. 9)

the desired coverage area. By convention the master is labelled "M" and the secondaries designated "W", "X", "Y" and "Z", respectively. Every station in the chain transmits groups of pulses at a specified group repetition interval (GRI). See Figure 2-6 for an example. For each chain, a minimum GRI is selected of sufficient length so that it contains time for transmission of the pulse group from each station (10,000 microseconds for M; 8000 microseconds for each secondary)[54] plus time between each pulse group so that signals from two or more stations cannot overlap in time within the coverage area. With respect to the time of arrival of the master's signal, a secondary will then delay its own transmission for a specified time period (called secondary coding delay). Note that the GRI is timed to begin coincident with the start of the first pulse of the master group.

Each station transmits one pulse group per GRI. The master pulse group consists of eight pulses spaced 1000 microseconds apart and a ninth pulse 2000 microseconds after the eighth. Secondary pulse groups contain eight pulses spaced 1000 microseconds apart.[55] Multiple pulses are used so that more signal energy is available at the receiver thereby improving the signal-to-noise ratio (SNR) without having to increase the transmitters peak transmit power capability. The ninth pulse of the master's group is used to identify the master and to blink. Blinking, accomplished by turning the

[54] Ibid.

[55] Ibid.

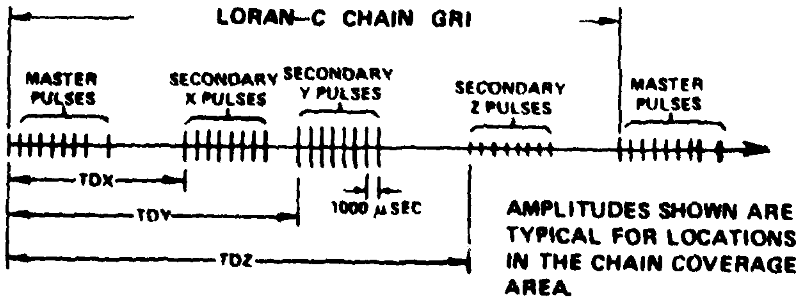


Figure 2-6 Example of Received LORAN-C Signal

(Source: Reference 12, p. 5)

ninth pulse off and on in a specific pattern (see Figure 2-7), is used to caution users that a particular station pair (for example XY) is out of tolerance and should not be used to obtain a fix. Secondary stations in the unusable pair also blink by turning the first two pulses on and off. In addition all transmitting stations are equipped with cesium frequency standards. These highly stable and extremely accurate timers allow every station to derive its own transmission time without referring to another station.

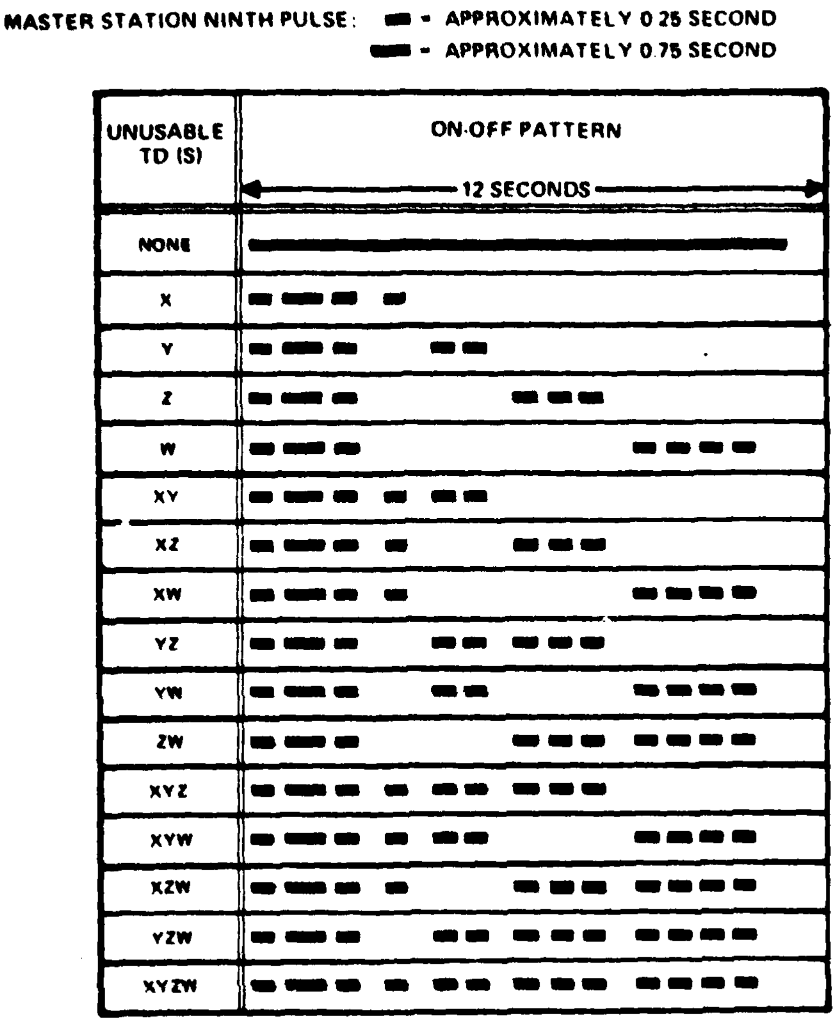
The objective in governing a LORAN-C chain is to maintain consistently the observed time difference of each master-slave pair throughout the coverage area. Time difference variations may occur because of frequency offsets in the cesium timers and changes in propagation conditions.[56] To detect these variations one or more SAM's are placed throughout the coverage area and equipped with precision receiving equipment. When the monitor(s) detects an intolerance greater than $\pm$ 200 nanoseconds, blink is ordered. LORAN-C has maintained a 99.7% reliability rate.[57] New LORAN Replacement Equipment (LRE) will raise this reliability even more.

Two added features of LORAN-C make it even more attractive. The first is a direct by-product of the inherent stability of the transmitted signals: cesium frequency standards permit use of the system as a very stable frequency reference. Users are then able to verify their chronometer accuracies to within

---

[56] Reference 11, p. 2-5.

[57] Reference 12, p. 10.



SECONDARY STATION FIRST TWO PULSES:

TURNED ON (BLINKED) FOR APPROXIMATELY 0.25 SECONDS EVERY 4.0 SECONDS. ALL SECONDARIES USE SAME CODE. AUTOMATICALLY RECOGNIZED BY MOST MODERN LORAN-C RECEIVERS.

Figure 2-7 LORAN-C Blink Code

(Source: Reference 12, p. 8)

several microseconds. The second is repeatability. A LORAN-C fix at a known location will usually vary less than 300 feet while in many areas this variation is less than 50 feet.[58] By recording readings at a particularly desirable location (profitable fishing ground, potential oil field), a navigator can return to the same position at any later date. This feature has great utility to many different users in the civil maritime community.

D. INTRODUCTION TO OMEGA

A major shortcoming to LORAN-C is the lack of world-wide coverage. Because of this drawback the U.S. Navy sponsored research, beginning in the 1950's, to find a replacement navigation system for LORAN-A with the accuracy of LORAN and the added benefit of global utilization. Experimentation in the VLF range, utilizing skywave propagation, demonstrated the feasibility of obtaining the above-mentioned requirements (skywaves at VLF are inherently stable and their travel times are easily predicted).[59] The culmination of this research was OMEGA. Some of the advantages that that system has are: global coverage (5000 to 6000 NM range with only eight transmitter sites); the 10-14 kHz band permits operation in a stable and predictable propagation environment; the long ranges at which the signals can be received usually permit selection of more than the two LOP's, minimum, required for a fix; and VLF

---

[58] Ibid., p. 14.

[59] Reference 13, p. 1.

signals are usable by submerged submarines.[60] The OMEGA system, when fully implemented, is designed to provide a world-wide all-weather navigation system for aircraft, surface vessels, and submarines, with nominal accuracies of one mile during the day and two miles at night.

E. HISTORY OF OMEGA

Professor J. A. Pierce of Harvard University, a prominent figure in the development of pulsed hyperbolic navigation systems, proposed in 1947 that continuous wave (CW) phase comparison systems receive more attention in the long range navigation field. The particular system that he was involved with along these lines came to be known as RADUX. This experimental system was intended to operate in the 40 to 50 kHz frequency range; operating ranges of 3000 NM with accuracy errors of 3 to 5 NM were seen to be obtainable. An experimental RADUX system was placed in the Pacific in test status with good results - 2000 mile range with ± 4 NM system accuracy for 90 percent of the time.[62] Meanwhile, Professor Pierce was continuing to measure the transmissions of a 16 kHz system (known as GBR RUBGY); the phase stability of the received carrier was quite remarkable, even at trans-Atlantic range. As a result of his observations a 10 kHz element was added to RADUX in 1955 that greatly increased the accuracy of RADUX

---

[60] Reference 14, p. 118.

[61] Reference 13, p. 1.

[62] Reference 14, p. 119.

(better than ± 1 NM at RADUX operating ranges).[63] The VLF component became known as OMEGA; the twin system became RADUX-OMEGA.

Further research led the developers to the conclusion that the RADUX portion of the system was, in effect, a less efficient mode: it's range was less than 3000 NM thus requiring too many transmitter sites (35) for global coverage. OMEGA ranges were on the order of 5000 to 6000 NM and global OMEGA coverage required only 8 transmitter sites.[64] As a result, in 1957 the decision was made to concentrate all efforts towards development of a total VLF system that would operate in the 10-14 kHz range already allocated to radio navigation. Work was still required in solving some lane ambiguity problems (discussed below) and transmitter site selections had to be made.

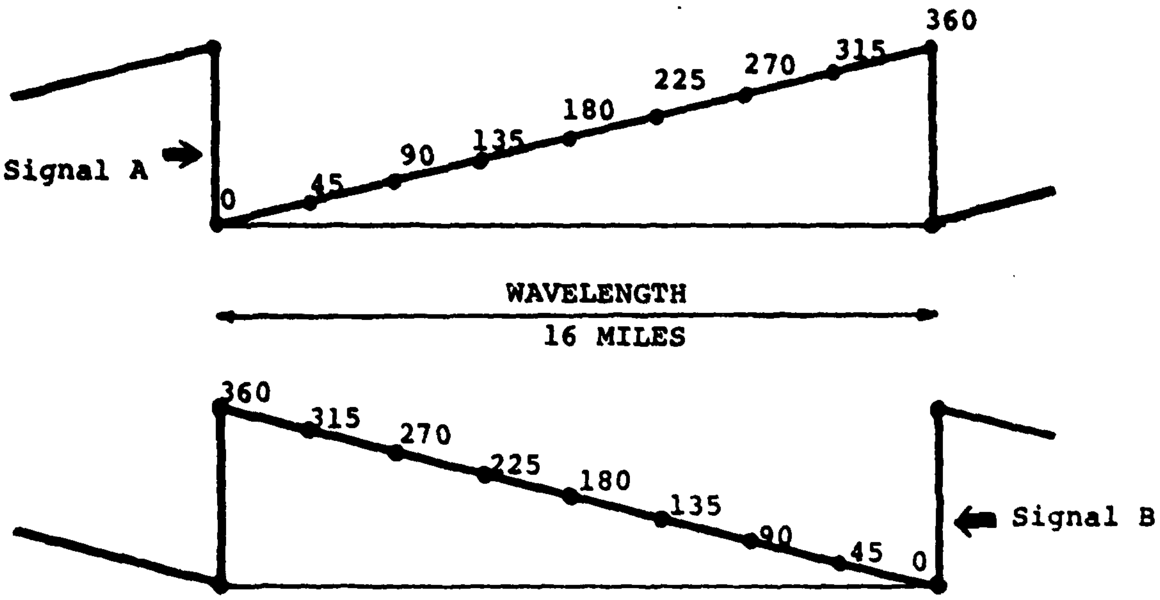
F. THE OMEGA SYSTEM

As mentioned before, OMEGA is a VLF hyperbolic system that utilizes phase difference measurements of CW radio signals. It differs from other hyperbolic systems that use a time-difference technique instead. The OMEGA measurement is the phase-difference of a 10.2 kHz signal transmitted from two stations (See Figure 2-8). The phase difference measurement then yields a hyperbolic LOP. The wavelength of the 10.2 kHz signal is nearly 16 miles; the phase measuring readings repeat

---

[63] Ibid.

[64] Ibid., p. 120.



Phase Signal A	0	45	90	135	180	225	270	315	360
Phase Signal B	360	315	270	225	180	135	90	45	0
Phase Difference	0	90	180	270	360	90	180	270	0

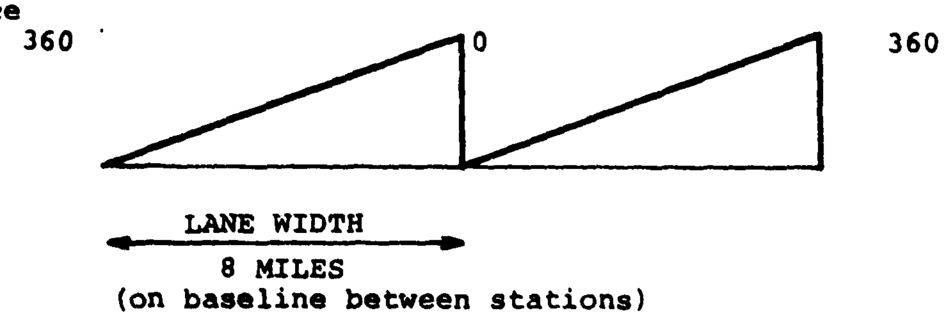


Figure 2-8 OMEGA Phase Difference Measurement

(Source: Reference 4, p. 528)

twice per wavelength (or every eight miles). Each of these eight mile intervals is called a lane (See Figure 2-9).[65] The measured phase difference yields an LOP within a lane; Oceanographic Office OMEGA charts are printed with numbered lanes. To use the system, a navigator sets the counters on the OMEGA receiver at the beginning of the voyage; as the vessel proceeds the number of lanes traversed are recorded (more sophisticated, and costly, receivers exist which do not require prior knowledge of position).

Relative times of signal transmission of OMEGA stations must be determined with a high degree of accuracy (hyperbolic systems measure distances radio waves travel in units of time). Each OMEGA station transmits, in turn, a signal of one second duration every ten seconds (all of which are phase-locked to a common time standard-nominally Universal Time)(See Figure 2-10).[66] OMEGA combines aspects of both pulse and CW transmissions. OMEGA measurements are of the relative phase of bursts of a CW carrier, transmitted at different times in the same frequency. The use of a single frequency is advantageous since it remains the same for all signals. Each OMEGA site then transmits in a fixed sequential pattern so that only one signal is sent at a time. OMEGA receivers identify each station by the location within the sequence and by the length of time of the signal. Another distinction of the OMEGA system is that LOP's can be determined from any two stations that are

---

[65] Reference 4, p. 527.

[66] Reference 13, p. 1.

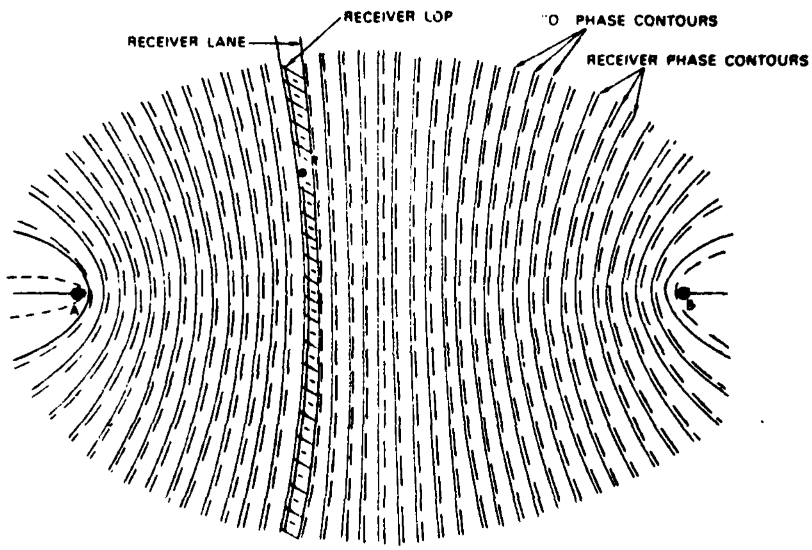


Figure 2-9 OMEGA Lane Pattern

(Source: Reference 4, p. 529)

		START			10 SECONDS				END	START
TRANSMISSION INTERVAL		.9	1.0	1.1	1.	1.1	.9	1.2	1.0	.9
STATION	1	10.2	13.6	11.33	$-f_1$					10.2
	2	f_2	10.2	13.6	11.33	$-f_2$				
	3		f_3	10.2	13.6	11.33	f_3			
	4			f_4	10.2	13.6	11.33	$-f_4$		
	5				f_5	10.2	3.6	11.33	$-f_5$	
	6					$-f_6$	10.2	13.6	11.33	f_6
	7	11.33					f_7	10.2	13.6	11.33
	8	13.6	11.33					f_8	10.2	13.6

> <
.2 second
separation

Figure 2-10 OMEGA Signal Format

(Source: Reference 4, p. 528)

transmitting signals that can be received. Thus the navigator can be selective in choosing signals that will yield the most accurate fix. Given the eight station network envisioned by OMEGA, at least four stations should normally be available to the navigator anywhere on earth. From these four stations a minimum of six possible LOP's are obtainable.[67]

Present system geometry includes seven operating stations usable for navigation with the eighth scheduled for operation by 1980. The seven are located in Norway, Liberia, North Dakota, Hawaii, La Reunion Island, Argentina and Japan.[68] The eighth will be located in Australia (at present a temporary station located in Trinidad, West Indies, is transmitting and will cease operations upon commencement of the Australian station). Since 1967 the U.S. Navy has been responsible for the implementation of the world-wide OMEGA system. In mid-1978, the USCG assumed responsibility for operating the two U.S. stations and for contracting operation of the stations in Trinddad and Liberia (subject to reimbursement by the Navy).[69] The other system stations are operated by the host nations under various basic bilateral agreements between the U.S. and the partner nation.

In a joint DOD/DOT agreement signed in 1974, OMEGA was endorsed as "the radionavigation system for worldwide, enroute,

---

[67] Reference 4, p. 529.

[68] Reference 8, p. 3-6.

[69] Ibid.

general-purpose use.[70] It is very useful in those oceanic regions, not covered by LORAN, where its accuracies are permissible for safe navigation. At the present time the seven operating stations are providing basic coverage of over 90 percent of the earth's surface; the Northern Hemisphere is virtually 100 percent served. The system has not yet been declared fully operational world-wide, owing to the incomplete status of the Australian station. Regional validation has been taking place as coverage and accuracy data are recorded and collated for each geographic area. Full operational status is expected sometime in 1982.[71]

---

[70] Reference 15, p. 40.

[71] Reference 8, p. 3-7.

III. SATELLITE NAVIGATION

A. BACKGROUND

The idea of using man-made satellites to navigate the oceans of earth dates back to the Sputnik era, when the Soviets launched the first artificial satellite, Sputnik 1, on October 4, 1957. During this same period the need developed for the accurate revision of position information for the inertial navigation gear aboard Polaris submarines. Thus need and technology came together. Drs. William Guier and George Weiffenbach of the Applied Physics Laboratory (APL) of Johns Hopkins University became very interested in the substantial Doppler frequency shift of radio signals from Sputnik.[72] Doppler shift refers to the apparent change in frequency of radio waves received when the distance between the signal source (the satellite) and the earth-side receiver is either increasing or decreasing due to the motion of either or both.[73] The degree of shift is proportional to the velocity of approach or recession: frequency shifts up as the satellite approaches the receiver and shifts down as the satellite arrives at and passes beyond the receiver. If the navigator knows the position of the satellite (its orbit) and is able to measure the Doppler shift very accurately, then the receiver's location on earth can be determined.

---

[72] Reference 16, p. 1.

[73] Reference 4, p. 580.

These APL scientists laid the groundwork for this theoretical system by deriving algorithms which would provide solutions to the entire satellite orbit determination problem, utilizing a single tracking station earthside taking accurate Doppler measurements. Following their success, several other scientists at APL (Drs. Frank McClure and Richard Kershner) developed the notion of inverting the process to determine the navigator's position with Doppler measurements of a satellite with a known accurate orbit. The application of this theory of Doppler measurement led to the funding of the first satellite navigation system in the U.S. Sponsored by the U.S. Navy, the Navy Navigation Satellite System (NAVSAT), originally known as Project TRANSIT, came into being in order to fulfill a specific requirement set forth by the Chief of Naval Operations: "Develop a satellite system to provide accurate, all weather, world-wide navigation for naval surface ships, aircraft and submarines".[74] TRANSIT became operational in January, 1964; in July, 1967, it was released to the civil community for commercial use.[75]

While TRANSIT was proving the value of satellite systems, other programs were conducting research along parallel avenues in the 1960's. The Time Navigation Program (TIMATION) advanced the technology utilizing highly stable atomic "clocks" and investigated alternatives to the Doppler methods employed in

---

[74] Ibid.

[75] Reference 16, p. 2.

TRANSIT. The U.S. Air Forces' "621 B" program was the basis for investigation into the confirmation of the means for accurate three-dimensional navigation. All these various fields of endeavor melded in 1973 when the concept of NAVSTAR GPS (Navigation System using Timing and Ranging Global Positioning System) was formulated. In the ensuing years, the concept has been demonstrated to provide, successfully, highly accurate 3-D navigation information to mobile users. A six satellite constellation has been maintained to provide a test system on the West Coast. Test results to date have generally exceeded anticipated performance (and will be discussed later); as a result the program passed, in principle, the DSARC II milestone in early summer, 1979, and the program went from the Demonstration/Validation phase to the Engineering Development phase. By mid-summer 1979 actual implementation-spending money-had not yet begun, though funding was anticipated by mid-August.[76] In addition, contracts for user equipment competition have been let to Collins and Magnavox for prototype competition.[77]

This chapter will examine both the TRANSIT and the NAVSTAR systems; TRANSIT because it is an operational system presently employed by civil maritime users and NAVSTAR because its potential to replace TRANSIT and other systems is great. The emphasis will be placed on NAVSTAR however, because of the assumption stated earlier in Chapter I of this thesis that

---

[76] Reference 17.

[77] Ibid.

NAVSTAR represents a potential replacement system for LORAN-C/OMEGA. Test results will be presented in the following chapter; the ensuing presentation will examine the theory and concepts of the system as it is presently conceived. It should be noted that the system is still open to changes; thus some items mentioned in this chapter may not bear out in the establishment of NAVSTAR as an operational system. However, this presentation is an accurate review of the program up to the summer of 1979.

B. THE TRANSIT SYSTEM

TRANSIT, in its present form, consists of five satellites in circular polar orbits; four tracking stations located in Wahiawa, Hawaii, Pt. Mugu, California, Rosemount, Minnesota and Prospect Harbor, Maine;[78] a computing and control center colocated at Pt. Mugu, and injection stations (which transmit data to the satellites) colocated at the Point Mugu and Rosemount sites. The satellites orbit the earth every 107 minutes at an altitude of approximately 1075 kilometers.[79] Their constellation of orbits forms a "birdcage" within which rotates the earth. Within each satellite are two main components: a very precise frequency standard which "drives" the two radio transmitters at 150 MHz and 400 MHz (as well as a counter which acts as the satellite's clock) and a core memory which maintains the current ephemeris of the satellite.

---

[78] Reference 18, p. 11.

[79] Reference 16, p. 5.

The ephemeris contains the celestial position information of the space vehicle. The satellites are solar-cell powered and stabilized so that the antenna is always pointing toward the earth. Only one satellite is used to fix the navigator's position: the satellite transmits data every two minutes earthside and its stored information is upgraded every 12 hours even though it has a 16 hour storage capacity.[80] The information broadcasted by the satellite includes its own ephemerides (variables describing its own orbit) plus a time reference.

The four tracking stations follow the signal of the satellite at every opportunity. The tracking process consists of measuring the frequency of the satellite signal at 4 second intervals. Typically a satellite will be visible to a tracking site during a 17 minute period from rise to set.[81] Once the satellite is no longer visible, the tracking information is relayed to the computing facility. The computing center accumulates all the various tracking data and at least once a day it: (1) computes revised orbit information and updates the ephemeris for each satellite for the next 16 hours; (2) computes corrections to the satellite clock in order to correct for oscillator drift; and (3) performs calibration of all earth-side system oscillators and clocks.[82] Once this information is calculated at the computing facility it is transmitted

---

[80] Reference 4, p. 581.

[81] Reference 18, p. 11.

[82] Ibid.

to the injection station, which has the responsibility of inserting the data into the satellite's memory. A navigator desiring to fix a position using TRANSIT must measure the received frequency at specific intervals and must then demodulate the satellite's carrier signal to obtain the satellite orbit information. Knowing the orbit information, frequency and approximate position, the actual fix position of the ship can be readily determined using a small digital computer usually incorporated into the receiver.

A satellite fix is obtainable whenever the maximum altitude of the satellite, relative to the navigator, is between 15 and 75 degrees. Usually, each satellite will provide 4 fixes per day (two on successive 107 minute orbits and two more some 8 to 12 hours later, again on successive orbits). This is because of the difference between the earth's rotation (which carries the navigator under the satellite's orbit every 12 hours) and the period of the satellite's orbit, which is approximately 107 minutes.[83] As a result, satellite availability increases as the user travels to the higher latitudes and decreases approaching the equator. The actual fix is accomplished by using the receiver's computer and is based on the Doppler range counts that take place as the relative distance between a transmitter and receiver changes. This change takes place when the satellite, transmitting its signal orbits past the receiver aboard the ship or other platform.

[83] Reference 4, p. 582.

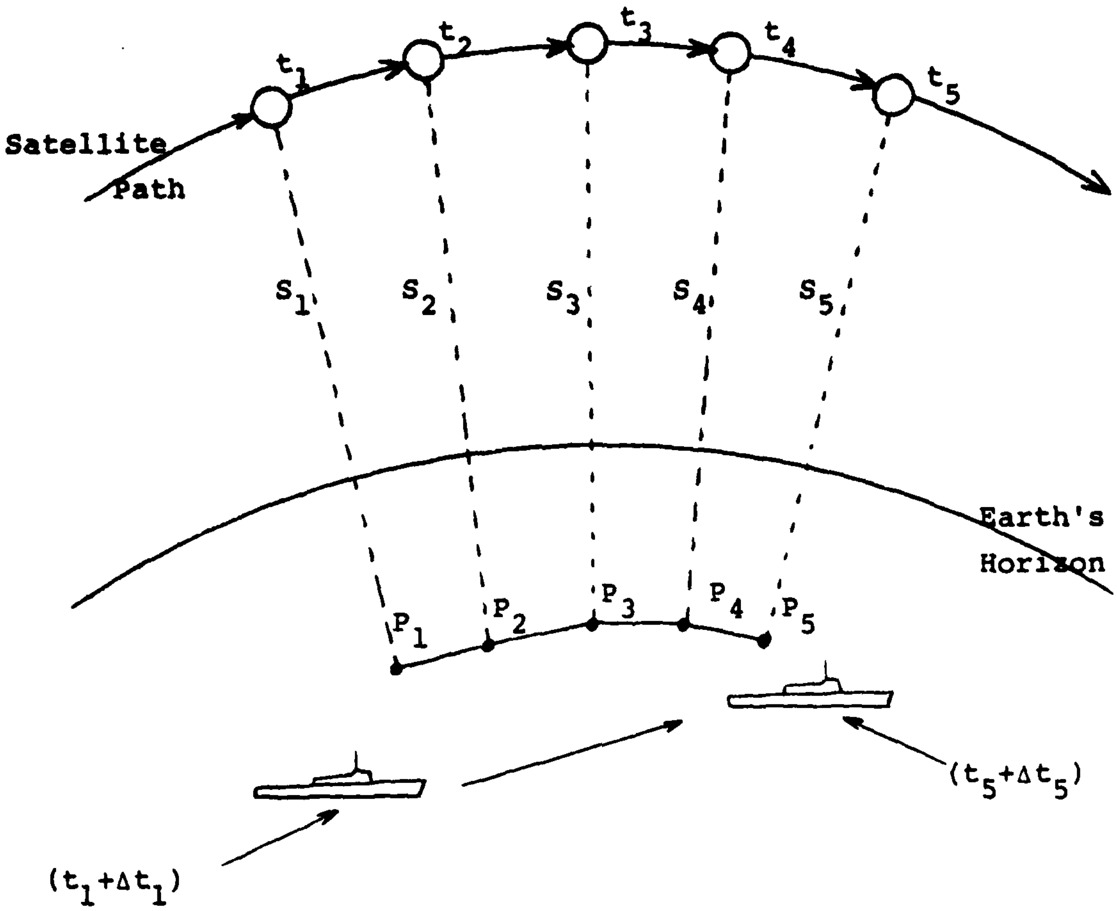
The distance change consists of the satellite's motion in orbit, the ship's motion on the earth's surface and the earth's axial rotation - all of which contribute to the Doppler shift.

Figure 3-1 describes, in simplistic terms, the time, range and position relationships used in the fix acquisition process. Times t_1 through t_5 are the satellite positions, in orbit, at the times of transmission of the signal (these occur at approximately two minute intervals). S_1 through S_5 are the ranges between ship and satellite. P_1 through P_5 are the ship's positions when the navigation receiver picks up the satellite's synchronization signal, represented by $(t_1 + \Delta t_1)$ through $(t_5 + \Delta t_5)$. Δt is the interval of time required for the signal to propagate from the satellite to the shipboard receiver. Figure 3-2 depicts the integral Doppler measurements. These are: the count N_{1-2} of the number of cycles (N_3) received between $(t_1 + \Delta t_1)$ and $(t_2 + \Delta t_2)$, the count N_{2-3} of the number of Doppler cycles between $(t_2 + \Delta t_2)$ and $(t_3 + \Delta t_3)$,[84] etc., for all 2 minute intervals that occur during the passage of the satellite over the ship's receiver. The fix taking process requires that four or five 2 minute Doppler counts be taken during the passage of the satellite. The counts are then combined with the satellite ephermeris message and fed to the digital computer, which then compares calculated position to estimated ship's position, repeatedly, until a solution converges.[85]

---

[84] Reference 4, p. 587.

[85] Ibid.



$S_1 - S_5$: ranges between ship and satellite

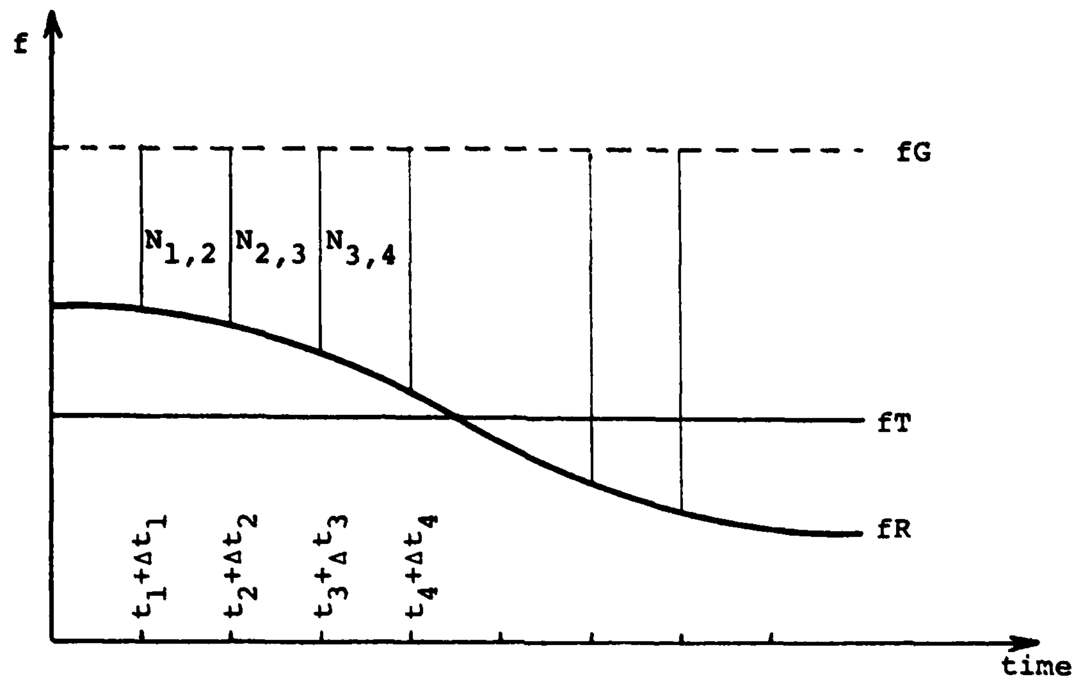
$P_1 - P_5$: ship's position

$(t_1+\Delta t_1) - (t_5+\Delta t_5)$: satellite synchronization signal

Δt: time interval satellite signal propagates from satellite to ship's receiver.

Figure 3-1 Transit Fix Process

(Source: Reference 4, p. 586)



f = frequency

fG = navigator's reference frequency (400 MHz)

fT = satellite transmission frequency (399.968 MHz)

fR = received frequency

Figure 3-2 Transit Integral Doppler Measurements

(Source: Reference 4, p. 587)

TRANSIT has been operating successfully for over fifteen years, to date. The system's reliability and availability have achieved some remarkable levels of performance. For example, between 1964 and 1977, 32,389 message injection attempts (from injection site to satellite) were made. Of these only 7 were verified as less than 100% successful, and all 7 were verified as successful on the next orbit of the satellite.[86] The satellites themselves have also done extremely well. Designed for an approximate life span of 5 years, three of the five operational vehicles (launched in the late 1960's) were performing flawlessly after more than 10 years in orbit.[87] In case problems do arise there are twelve back-up "birds" stored in New Jersey as system back-ups. An added feature of the TRANSIT satellite is the light weight (61 kilograms or 134 pounds) of the vehicle. This permits launching TRANSIT replacement satellites with relatively inexpensive solid fuel Scout rockets. In addition, a new generation of satellite will be produced in limited numbers. Called NOVA, these new vehicles will enhance TRANSIT by eliminating atmospheric drag which affects orbit prediction calculations, increasing received signal levels, and increasing onboard memory and computation levels.[88]

---

[86] Reference 18, p. 36.

[87] Ibid., p. 37.

[88] Ibid., p. 39.

C. NAVSTAR GPS

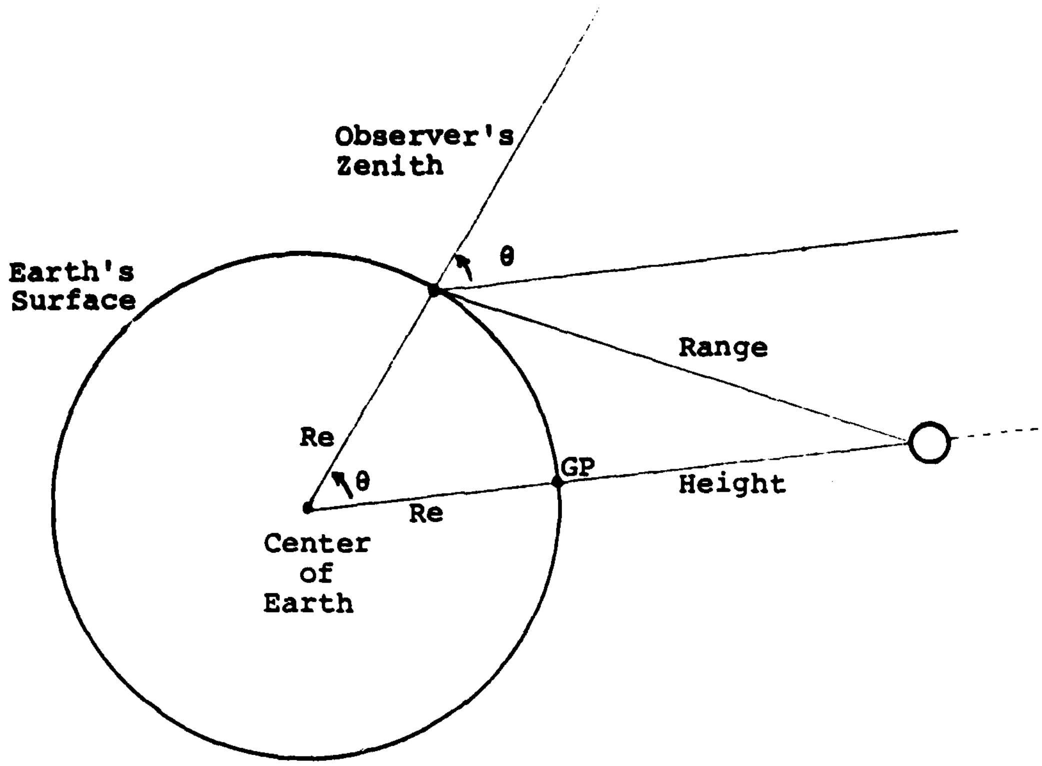
As mentioned earlier, the Navigation Technology Program at the Naval Research Laboratory (NRL) came into being with the merger of the U.S. Air Force's 621 B Project and the U.S. Navy's TIMATION Porgram in 1973.[89] These two projects had been established to do research into a satellite passive ranging system that would satisfy the U.S. Armed Forces multiple navigation needs. The Navy program actually entailed launching satellites, while the Air Force used ground stations to simulate satellite-type ranging signals to appropriately-equipped aircraft. Each of these programs provided much input into the now very successful NAVSTAR GPS program. Various technological and economic factors, such as the Space Shuttle Program and the always-advancing electronics technology, have lowered costs for the NAVSTAR program to an affordable range. NAVSTAR GPS, in its present form, will provide highly accurate timing and positioning information in three dimensions to users located anywhere near the surface of the earth (within 600 KM) or on it.[90] The system consists of three major segments - space, control, and user - which will be discussed further in this chapter.

The technique employed in the passive ranging scheme of NAVSTAR utilizes known satellite distances to solve the basic navigation equation. Figure 3-3 presents the basic navigation

---

[89] Reference 19, p. 107.

[90] Reference 20, p. 2.



Re: earth's radius

GP: geographical position of celestial body (apparent position of satellite on surface of earth)

θ : meridian angle

Figure 3-3 The Navigation Triangle

(Source: Reference 4, p. 352-59)

triangle, applied to the satellite environment. R_e (earth's radius) is known, as is the height of the satellite above the center of the earth. The distance between the observer and the satellite (labelled RANGE), is measurable, electronically. Because of the geometry of the triangle, the RANGE line forms an LOP on the surface of the earth, and two or more LOP's will yield a fix. This concept, based on TIMATION efforts, is depicted simplistically in Figure 3-4. Precise ranges (R_1 and R_2 in the figure) are determined from two or more satellites and the fix is subsequently computed. To make passive ranging viable, precise orbit information of the satellite must be known, highly accurate clocks and stable oscillators must be part of the system and synchronization of satellite and user clocks must take place.[91]

TIMATION proved the feasibility of this passive ranging scheme through a series of satellites called TIMATION I and II, launched in May, 1967 and September, 1969 respectively.[92] Further information was gathered with the launch of the third satellite in the series (in July 1974), renamed Navigation Technology Satellite ONE (NTS-1) to signify the inception of the NAVSTAR program. The principal difference of NTS-1 from the earlier satellites was the incorporation of several rubidium clocks, which provided a stability on the order of one part in 10^{12} per day. NTS-2 was launched in June 1977; its significance was that it was the first satellite totally

---

[91] Reference 20, p. 108.

[92] Ibid., p. 109.

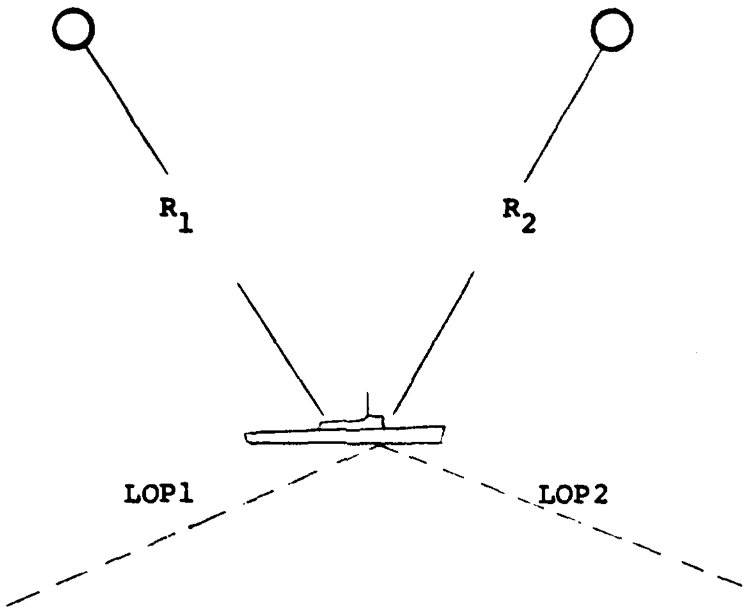


Figure 3-4 Timation Navigation Concept

(Source: Reference 18, p. 108)

under the auspices of the NAVSTAR GPS program. Cesium standards were used instead of rubidium, with a correspondingly more accurate level of stability.[93] Finally, an NTS-3 is planned for a 1981 launch. Further experiments are planned to validate equipment and concepts, just as the previous satellites validated various aspects of the GPS system.

As mentioned earlier, the NAVSTAR GPS program is divided into three units: space, user and control segments. The Space Segment will consist of a constellation of 24 satellites, with 8 satellites each in 3 circular, 12-hour orbits, at an altitude of approximately 20,183 kilometers (km) or 10,898 NM.[94] This constellation is intended to provide user visibility of from 6 to 11 satellites anywhere in the world. Each satellite will transmit signals at two L-band frequencies (1575 and 1227 MHz) to allow for signal propagation time delays due to ionospheric effects and to minimize frequency allocation problems.[95] Each frequency will be modulated by a P (precision) code and a C/A (course acquisition) code.[96] The C/A code will allow the user to lock onto the signal very easily while the P code will permit precise time measurements and higher levels of accuracy. The two frequencies, L_1 and L_2, are spread spectrum pseudo random noise (PRN) signals; the PRN sequencing "spreads" the navigation signal over a band approximately 20

---

[93] Ibid., p. 112.

[94] Reference 21, p. 95.

[95] Reference 20, p. 3.

[96] Reference 21, p. 95.

megahertz (MHz) wide. Within this signal framework there is a 50 bit per second (bps) data message containing such information as satellite status and ephermeris, time synchronization and propagation delay corrections.[97]

Each satellite in the constellation will weigh approximately 446 kg (982 pounds) and will have a designed life expectancy of 5 years. They will be powered by solar arrays continually tracking the sun; nickel-cadmium batteries will be used during periods of eclipse. The satellites will be three-axis stabilized (meaning not spinning) and an on-board hydrazine propulsion system will be used for station keeping maneuvers. Satellite launches through 1983 will be accomplished with ATLAS E/F rockets.[98] Thereafter, it is anticipated that the Space Transportation System (STS), or Space Shuttle as it is commonly referred to, will be the means used to accomplish satellite orbit.

The control segment will consist of the Master Control Station (MCS), to be located at Fortuna, North Dakota (or Vandenburg, California), at least four widely separated monitor stations (MS) located throughout the world, and a Ground Control Station (GCS) colocated at NCC (as well as an alternate GCS colocated at one of the monitor sites).[99] The monitor stations are intended to track the satellites passively, in order to gather range data via the navigation signals. The

---

[97] Ibid., p. 99.

[98] Reference 20, p. 3.

[99] Ibid.

location of these monitors has yet to be firmly determined; however, efforts are being made to secure agreements with interested countries having the appropriate geographic location (higher altitudes).[100] The monitor stations will then transmit the collected ranging information, along with status and meteorological data, to the MCS. The MCS will function as a processing center, analyzing all the incoming data from the monitors in order to predict the best value of each satellite's velocity, acceleration, position and vehicle oscillator drift relative to GPS time. The generation of the information is necessary in order to revise, continually, and update the accuracy of future navigation messages to be transmitted back up to each satellite. The GCS will serve as the "upload" element of the system, transmitting the navigation message from NCC to the satellites. This uploading will take place at least once during each 12 hour period required for the satellite to orbit the earth.

Within NAVSTAR GPS, time requirements will be sustained through GPS System Time, which will differ from Universal Coordinated Time (UCT). UCT must be adjusted at regular end-of-year intervals to account for leap seconds; this adjustment would upset the availability of the satellite's signal to the user which would prove deleterious to the system's navigation support. GPS time will be maintained by MCS using a set of

---

[100] Ibid.

[101] Reference 21, p. 97.

very accurate cessium time standards. The difference between GPS time and UCT time will be less than 100 microseconds and will be regularly published to advise users who will use GPS as a time standard.[102]

The third portion of the NAVSTAR system is the User segment. The typical user equipments will consist of an antenna, receiver, data processor (including software), and control/ display unit. The receiver will measure pseudo-range and pseudo-range-rate (explained below) utilizing the navigation signals from at least 4 satellites. The data processor will then convert this information to three-dimensional velocity and position, as well as system time. The position information will be developed in World Geodetic System (WGS) coordinates. This is an earth-fixed earth-centered coordinate system which provides, irrespective of location on the earth's surface, "common-grid" information to the user.[103] Then, depending on the needs of the user, the position information will be displayed in any one of several types of coordinate systems.

As previously noted, four satellites are required to obtain a navigational fix. The use of 4 satellites removes the need for the user to employ a stable atomic clock; rather, the user equipment has an imprecise clock and employs clock correction data from the satellite. The user will be able to manually select the best four space vehicles or permit the receiver to

---

[102] Ibid.

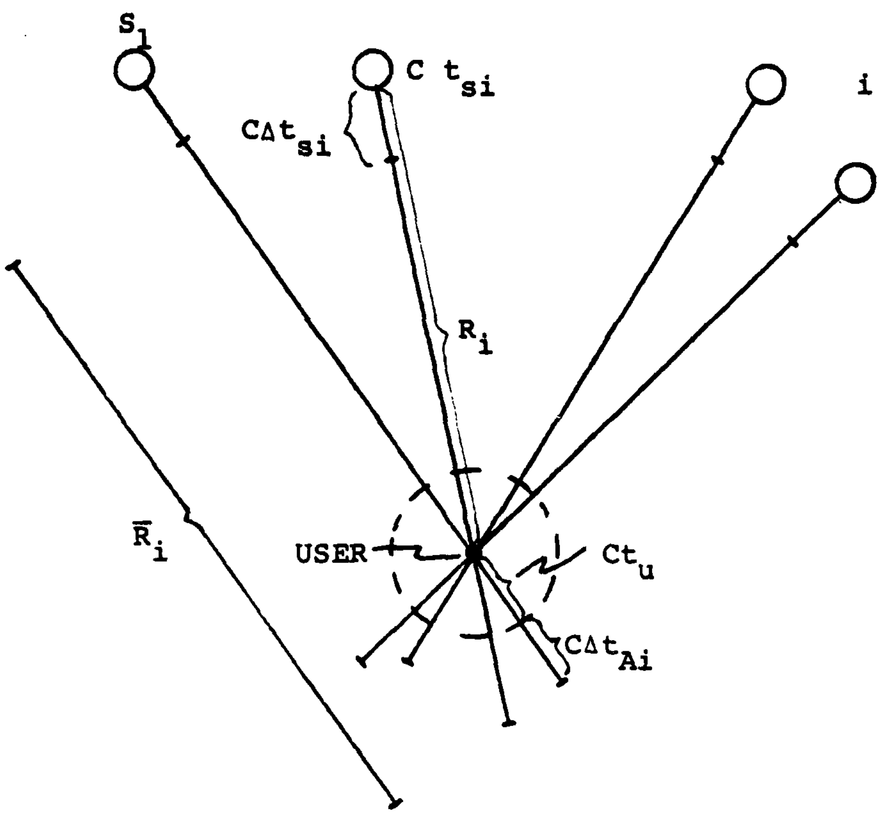
[103] Reference 20, p. 4.

select the best four space vehicles or permit the receiver to select them automatically. The receiver will then measure the pseudo-range to all four satellites. Pseudo-range is a range to the satellite, not equal to the true range, which contains a bias due to the user's imprecise clock (see Figure 3-5) as well as to propagation delays and other errors. It is measured by comparing the user's time reference with the satellite's time difference and observing the difference in phase between the two. In addition, velocity measurements, another feature of the system, are made by measuring the doppler shift in the carrier frequency of satellite's navigation signal.[104] Figure 3-6 provides data on anticipated position and velocity error distributions worldwide.

Up to this point, this thesis has presented the basic operating format of several systems currently in use or planned for use by user communities that include the civil maritime industry. In the case of NAVSTAR GPS, a committment has already been made to permit availability of the C/A code. The question remaining is to what accuracy will this availability extend. Here arises some tactical and strategic considerations which are beyond the scope of this presentation. Now that the reader has an understanding of the competing systems the next step is to analyze the issues - fiscal, political and engineering - surrounding the navigation problem.

---

[104] Ibid.



i = Space Vehicle

R_i = True Range

$\bar{R}_i$ = Pseudo Range

C = speed of light

$C\Delta t_{si}$ = i th satellite clock offset from GPS time

$C\Delta t_u$ = user clock offset

$C\Delta t_{Ai}$ = propagation delays and other errors

Figure 3-5 NAVSTAR Pseudo-Range

(Source: Reference 21, p. 96)

	HORIZONTAL		VERTICAL		
	User Error (meters)	User Error (feet)	User Error (M)	User Error (ft)	Time (nanosec)
50th percentile	4.1-7.2	14-24	5-8.8	16-29	8-15
90th percentile	7.9-13.8	26-45	12.9-22.5	42-74	23-40

Velocity Errors*

	Horizontal Velocity Error		Vertical Velocity Error	
	mps	fps	mps	fps
50th percentile	.07	.2	.08	.3
90th percentile	.13	.4	.21	.7

* Based on .061 mps/.2 fps Range Rate Error.

Figure 3-6 Anticipated Position Error

(Source: Reference 21, p. 104)

IV. THE NAVIGATION SYSTEM DILEMMA

A. NAVIGATION ISSUES AND REQUIREMENTS

DOT's National Plan for Navigation (NPN) has set forth certain criteria for marine radionavigation. These include accuracy, availabilities, coverage reliability, non-ambiguity, capacity and cost.[105] Accuracy requirements for the high seas have been established at 2-4 nm, and for the CCZ at 0.25 nm. No requirements have been set for harbor and harbor entrance (HHE) areas, owing to the uniqueness of each area. However, NPN states that position accuracy on the order of 50 feet would probably be a requirement.[106] Continuous availability is desirable but not mandatory. Coverage is required wherever marine traffic exists. Capacity means that any navigation system permissible for general usage need have the capacity to serve any number of users within the area it serves. Non-ambiguity refers to the assurance that must be afforded every navigator regarding the degree of reliability of the navigation system and thus the lack of any position ambiguities. Finally, cost must be affordable by the various users, from corporate firms to independent fishermen.[107]

---

[105] Reference 8, p. B-17.

[106] Ibid., p. B-18.

[107] Ibid.

Given this set of criteria imposed on the Coast Guard, the navigation dilemma begins to present itself more completely. As shown in the previous system descriptions, and as will be reviewed later in this chapter, no navigation system presently in operational use in the U.S. can provide for all the criteria imposed by the NPN. However, Phase I test results of NAVSTAR GPS are pointing to this satellite-based system as a probable solution to the plethora of navigation systems, which GAO insists should be reduced in both numbers and costs. The NAVSTAR program has just completed Phase I testing, which demonstrated the system's feasibility and field tested and validated the concept. Phase II, the development segment, is scheduled to run through 1983, and will include the production of prototype user equipment. Phase III, to continue until about 1987, will be the production and deployment phase with full scale operation anticipated by late 1987.

A number of questions have been raised because of the NAVSTAR concept: Do technical problems exist which might preclude maritime use of NAVSTAR? How does GPS compare with the other navigation systems? Can GPS be used in every facet of marine navigation? What are receiver prices going to be, relative to LORAN and OMEGA? What should be the status of LORAN-C, OMEGA and TRANSIT after GPS is available? Many of these questions have been answered, at least to some extent and are presented later in this chapter under the heading of "NAVSTAR Phase I Test Results". However some require top level decisions due to national security considerations.

For instance, to what degree of accuracy will the C/A mode be made available to civil users, many of whom might likely be foreign nationals? The tactical and strategic implications of a precision navigation system must preclude the system being used against its developer. Therefore, steps need to be taken to insure that the C/A mode, while satisfying civil maritime navigation needs as much as possible, cannot and will not be used for precision targeting against the U.S. This trade-off already concerns some potential users in the civil maritime industry who foresee degradation of the C/A mode to a level commensurate with existing systems. This provides them with little or no impetus to make the switch to NAVSTAR.

GAO must enter the picture now. In a Report to the Congress (LCD-77-109 of 21 March 1979), the agency pointed to a growing number of navigation systems with their mounting costs and stated in effect that there was too much redundancy and wasted monies. GAO recommended much consolidation and elimination, assuming NAVSTAR lives up to its growing reputation. If GPS does evolve to be the national primary navigation system, it will have to account for the needs of a wide variety of users, not least of which are the numerous members of the civil maritime community.

In the meantime, while NAVSTAR continues to impress its developers and exceed many expectations, LORAN-C and OMEGA (along with the Navy's TRANSIT system) are viable programs operated by the USCG. These systems are becoming older, however, and attention must be paid to such items as LORAN-C

expansion, incorporation of latest technology into equipment, replacement of obsolete equipments, and wide-scale area calibration for OMEGA. The U.S. Coast Guard must look at the lack of LORAN-C coverage in such areas as North Alaska, the Carribean, as well as insufficient coverage in Hawaii with a new perspective. NAVSTAR is apparently arriving, as DOD will likely make GPS its primary navigation system, thereby reducing dependence on LORAN and OMEGA to a minimum. However, its arrival as an operational system is nearly a decade away, and even after GPS is implemented there will need to be an overlap period to observe its performance and verify to what level of acceptance GPS stabilizes within the various user communities. Some estimates give the late 1990's as the true start of wide-spread reliance on NAVSTAR. Therefore, the need for present Coast Guard navigation systems will exist for at least a decade or two more and the Service is federally mandated to provide for adequate and safe navigation throughout this period. To what level remains unanswered. Further studies, including various economic and social benefit analyses need to be conducted and more data gathered. The Coast Guard realizes this and the effort is being made in no uncertain terms. No answer exists today, however, and none is likely to be found in the near future.

B. SYSTEM COMPARISONS

The following section is intended to present a comparitive analysis of LORAN/OMEGA, TRANSIT and NAVSTAR GPS, in terms of navigational accuracy available to the maritime navigator (See

Figure 4-1). Emphasis will be placed on describing shortcomings of the systems under consideration, as it is these negative aspects which detract from optimal system performance and thus lessen the ability of the navigator to perform his/her duties. In order to present this analysis, a definition of "accuracy" must be decided upon. In terms of real-world operations, involving some form of navigation or position location, accuracy should involve some ability to identify or locate some geographic position. To this end several areas of performance should be considered in more detail. Specifically these areas include repeatability, distortion and instrument-geographic conversion.

Repeatability of the position fix information relates to the degree with which a navigator can return to the same location time and again. In the case of LORAN-C a navigator can return to the same time difference readings and be within]5-30 meters of his desired position.[108] Distortion is concerned with grid warp, that is, the amount of deformation of the navigation grid that takes place over some area.[109] In LORAN-C, the conductivity of the earth decreases the propagation velocity of the signal. This causes a grid warp known as secondary phase error. In satellite navigation, a grid warp arises because of the model used to predict the satellite's orbit relative to the earth's field of gravity.

---

108 Reference 22, p. 226.

109 Ibid., p. 227.

SYSTEM	DESCRIPTION	ACCURACY(95%)	REPEATABLE	FIX RATE	COVERAGE
LORAN-C	Pulsed Hyperbolic (90-110 KHz)	460 meters (SNR 1:3)	18-20 meters	25/sec	N. America W. Pac. W. Lant. Mediterranean
OMEGA	CW Hyperbolic (10-14 KHz)	2-4 NM	2-4 NM	1/10 sec	90% Global
TRANSIT	Satellite Doppler (150,400 MHz)	500 M	50 M	30 min.- 110 min.	Global
NAVSTAR GPS	Satellite UHF Passive Ranging (1200,1500 MHz)	20-38 M (Horizontal) 25-47 M (Vertical)	20-38 M (Horizontal) 25-47 M (Vertical)	contin- uous	Global

Figure 4-1 Navigation System Characteristics

(Source: Reference 20, p. 4)

The third factor in the consideration of accuracy is the means of converting instrument readings to geographic position. LORAN and OMEGA charts have time difference lines and lanes superimposed over geographic details, while NAVSTAR will provide a direct latitude/longitude reading. It is important then to keep these three parameters in mind when comparing one system to another in terms of degrading levels of accuracy.

1. LORAN-C

LORAN-C was chosen as the radionavigation system for use in the coastal waters of the United States because of its ability to meet the safety criteria for position accuracy of one-quarter mile in the continental shelf region. LORAN-C does exhibit some shortcomings, however. Coverage is one of the drawbacks, as indicated in Figure 2.3. Although the navigator can make good use of signals where they exist, only in a relatively small portion of the world can these signals be recovered. In terms of repeatability, LORAN-C is very good and in fact compares favorably to the NAVSTAR C/A mode. As indicated earlier, LORAN-C suffers from secondary phase error (a form of grid distortion) caused by the effects of the land mass on the navigational signal. However, these errors have been corrected for, via calibration tests over geographic areas, and are reflected on LORAN-C navigation charts. In this sense LORAN-C accuracy is enhanced; the potential for instrument to geographic position conversion becomes one of operator error and this factor can be minimized through training and experience. Two other factors which degrade LORAN-C are weather problems and interference from other signals.

Interference can often be overcome by making use of adjustable notch filters, though care must be taken to insure proper use of these by the operator. Weather factors such as static caused by mists or gentle rain are not as easily reconciled and do present difficulties to the navigator.

2. OMEGA

OMEGA was designed to provide world-wide coverage but it hasn't lived up to its earlier promises. With regard to repeatability, calibration efforts have determined that the OMEGA position wanders anywhere from 0.5 up to 2 or 3 miles, at a fixed position.[110] In addition, a number of other factors, such as lane count errors, ionospheric disturbances and wrong way signal reception, cannot always be anticipated. Sometimes, as a result, positional errors of 10 to 30 miles have been observed. Weather affects OMEGA in a fashion similar to the effect suffered by LORAN-C. Skywave corrections must also be incorporated into the fix taking process, thereby increasing the likelihood of greater positional error. Finally, phenomena such as polar cap anomalies (PCA's) and sudden ionospheric disturbances (SID's), as well as the combinations of long path reception and modal interference have precluded the use of certain transmitter stations in various parts of the world. Thus worldwide, continuous coverage is not provided by OMEGA.

---

[110] Ibid., p. 228.

3. TRANSIT

TRANSIT is now functioning as a viable satellit-based navigation system. It provides world-wide coverage and yields accurate fix information. However, when compared to NAVSTAR it does have some relative drawbacks. The signal from a TRANSIT satellite is not continuously available, as will be the case in NAVSTAR. TRANSIT utilizes five satellites in orbit approximately 10,900 km above the earth while NAVSTAR will have twenty-four "birds" orbitting at nearly twice the altitude. This means that a single TRANSIT satellite, though able to provide fix information on each pass, will only be in view of the navigator at various intervals spaced from 90 minutes apart up to several hours or more. In certain situations, such as navigating in restricted waters or along the coast, where fix information must be frequently updated, TRANSIT is unable to act alone and must be supported by other means. This can prove to be an unsatisfactory arrangement owing to the present expense of a TRANSIT receiver.

In terms of repeatability, a TRANSIT fix is competitive with NAVSTAR. The degradation occurs owing to the factor of unknown ship's velocity which, as mentioned earlier, is one of the variables in the TRANSIT navigation solution. Data shows that TRANSIT fix accuracy is on the order of approximately 0.1 nm,[111] which makes it more desirable in terms of fix accuracy than LORAN-C or OMEGA. However, with

---

[111] Ibid., p. 229.

the results of NAVSTAR testing coming to light, TRANSIT has been shown to be less accurate than NAVSTAR and lacks the important factor of continuous availability.

4. NAVSTAR GPS

In terms of future promise, NAVSTAR seems to resolve many of the shortcomings exhibited by the other systems under consideration. NAVSTAR offers world-wide coverage, not achieved or delivered by either LORAN, OMEGA or TRANSIT. It is relatively unaffected by weather and offers excellent repeatability-though it must again be pointed out that no final level of accuracy for civil use of the C/A mode has been firmly established (100-200 meters is often quoted by DOD).[112] Conversion from instrument readings to geographic position permits no system degradation due to human error as the receiver will yield fix information in direct latitude and longitude readout. An added benefit of the system's receiver is the pre-ordained requirement of an internal computer to carry out the complex computations. The presence of the computer will permit extra functions to be programmed into the receiver unit (such as self-diagnostics and testing, and adjusting to local chart information) at relatively little extra cost. The use of a computer will also help eliminate some of the human error.

---

[112] Ibid., p. 230.

C. NAVSTAR PHASE I TEST RESULTS

NAVSTAR GPS underwent an exhaustive series of field tests during the Defense Systems Acquisition Review Council (DSARC). These tests, known as Phase I: Developmental Test and Evaluation, were carried out from March, 1977 to June, 1979. During the process, 600 test missions were conducted, utilizing eleven types of host vehicles (See Figure 4-2) and 9 types of user equipment configurations.[113] In addition, CONTROL and SATELLITE segment performance tests were conducted separately with 22 major field test objectives being identified as items of interest to DSARC (See Figure 4-3 for this listing). Of special concern is Objective 12, Shipboard Operations, and Navigation Accuracy, which will be reviewed below.

Field tests were conducted almost entirely by various military organizations under the cognizance and direction of the GPS Joint Program Office located at USAF's Space and Missile Systems Organization (SAMSO), Los Angeles. Participating organizations included the USAF 4950th Test Wing, USN Pacific Missile Test Center, Naval Air Development Center, Naval Ocean Systems Center, USA Yuma Proving Ground, USA Operational Test and Evaluation Agency, Defense Mapping Agency, USA Electronic Proving Ground, USAF Avionics Laboratory, Naval Observatory, USAF Satellite Control Facility and the Naval Weapons Center.[114] Actual performance evaluation did not

---

[113] Reference 23, p. 2.

[114] Ibid.

TEST VEHICLES	PROVIDED BY	GPS SETS ONBOARD	DYNAMIC RANGE
Mobile Test Van	DMA	XU	STATIC
Man	ARMY	NP, MVUE	LOW
Landing Craft	NAVY	XU, YU	LOW
Frigate (FF1076)	NAVY	XU, YU	LOW
Armored Personnel Carrier	ARMY	MP, MVUE	LOW
M35 Truck	ARMY	XU, HDUE, MP, MVUE	LOW-MEDIUM
Jeep	ARMY	MP, MVUE	LOW-MEDIUM
UH1 Helicopter	ARMY	XU, YU, MP, HDUE, MVUE	MEDIUM
C141 AIRCRAFT	AIR FORCE	XU, XA, YU, YA, GDM, Z, HDUE	HIGH
P3 Aircraft	NAVY	XU, XA, YU, UA, Z	HIGH
F4 Aircraft	NAVY/AIR FORCE	XA	VERY HIGH

Figure 4-2 Phase I NAVSTAR Test Vehicles (Source: Reference 23, p. 3)

NAVIGATION ACCURACY:

1. Position Accuracy
2. Velocity Accuracy
3. Effects of Dynamics on ACC

DEMONSTRATIONS OF MILITARY VALUE:

4. Precision Weapon Delivery
5. Landing Approach
6. Rendezvous
7. Photomapping
8. Map-of-Earth Operations
9. Static Positioning
10. Combined Operations
11. Cross - Country
12. Shipboard Operations

THREAT PERFORMANCE:

13. Jamming Resistance
14. Selective Availability

ENVIRONMENTAL EFFECTS:

15. Prop & Rotor Modulation
16. Foliage Attenuation
17. Multipath Rejection
18. Ionospheric and Tropospheric Correction

SYSTEM CHARACTERISTICS:

19. Satellite Clock and Ephemeris Accuracy
20. Acquisition and Reacq. Time
21. Time Transfer
22. Signal Levels and Signal Structure

Figure 4-3 Major Field Test Objectives

(Source: Reference 23, p. 1)

commence until three satellites were launched into orbit in late 1978; and four satellites were available between January and May 1979. During this time, tests on various combinations of vehicles under widely varying conditions in performance of multiple types of missions were carrier out. Participating competing contractors included General Dynamics, Aerospace Corporation, Magnavox, Texas Instruments and Rockwell Collins. The final user field test report on navigation accuracy was published on 25 June 1979. Figure 4-4 lists the cumulative Position Error statistics. The various user equipments are briefly presented in Figure 4-5.

In terms of position accuracy NAVSTAR GPS has performed much better than originally anticipated. Early in the testing, before satellites were available, ground transmitters were used as signal sources for system checks and navigation tests. Once the satellites were deployed, position errors were reduced by 30 to 50 percent. Because the performance of GPS is ultimately given in terms of position and velocity error, data analysis was used to describe the statistical behavior of these errors. Information in the final field test reports was presented in terms of standard deviation, error means, circular and spherical probable error and cumulative characteristics. However, only cumulative values have been detailed in this presentation; the reader is referred to the appropriate technical report for a detailed summary of the statistical data.

Of major interest to civil maritime industry members are the Phase I test results for shipboard ope·ations. This final

USER EQUIPMENT	NUMBER OF MISSIONS	50TH PERCENTILE POINT(meters)	90TH PERCENTILE POINT(meters)
X	14	9.5	16.5
X-Aided	18	10.0	18.0
Y	6	14.0	27.0
Z	4	16.1	37.0
Manpack	15	13.0	28.0
HDUE	11	12.0	18.0
MVUE	8	14.6	25.5
All User Equipment	76	11.1	22.0

Figure 4-4 Cumulative Position Error Statistics by User Equipment

(Source: Reference 23, p. 5-1)

USER SET	DESCRIPTION
<u>X-SET</u>	High dynamic environment, used in severe hostile jamming situation 4 satellite channels for rapid signal acquisition. Has auxiliary sensor capability, can use Intertial Measurement Unit (IMU).
<u>HDUE</u>	"High Dynamic User Equipment" Alternate X-SET. Uses 5 channels. Texas Instruments developed.
<u>Y-SET</u>	Medium Dynamic user environment. Single satellite receive channel sequences between various satellites.
<u>MP/MVUE</u>	Manpack/Manpack/Vehicular User Equipment. Low dynamics, sequential tracking, configured for small size, weight, battery power and jam resistant.
<u>Z-SET</u>	Low dynamic environment, lowest cost due to deliberate compromise. Operate in C/A mode only, in non-hostile environment. No auxiliary sensor capability. Meets "swap-out" criteria for DoD TACAN.

Figure 4-5 User Equipment

(Source: Reference 24, p. 4)

field test report was published 1 June 1979 and details the information gathered from trials conducted on board the USS FANNING (FF 1076) and a U.S. Navy Landing Craft (LCU 1618). Equipment tested on board these two vessels included a 4-channel X-set (simultaneous reception) and a 1-channel Y-set (sequential reception). All equipment was mounted in a portable, weatherproof, palletized shelter and loaded by crane aboard each vessel. Tests were conducted aboard the LCU in December, 1978, when only 3 satellites were in orbit and aboard FANNING in January-February 1979, when a 4 satellite constellation was available.[115]

During LCU tests, NAVSTAR results were constantly compared against a precise "truth" reference, employed only for cross-checking navigation accuracy. A Motorola Mini-Ranger system was utilized with transponders placed at four sites on San Clemente Island. The LCU carried equipment on board as well; the GPS and Mini-Ranger antennas were positioned near one another facilitating comparison of navigation data. The LCU then operated in a racetrack pattern around the island gathering approximately three hours of 3-satellite data each day.[116] Both the X and Y sets operated in remarkable agreement with one another and the X and Y sets compared favorably with the Mini-Ranger system. A summary of horizontal error is provided in Figure 4-6. It should be noted that some error excursion was observed during the period of time when all

---

[115] Reference 25. p. 2.

[116] Ibid.

USER EQUIPMENT	DATE	AVERAGE HORIZONTAL POSITION ERROR (METERS)	AVERAGE HORIZONTAL VELOCITY ERROR (METERS/SECOND)
X-UNAIDED	6 DEC 78	7.7	0.28
	7 DEC 78	24.9	0.34
	8 DEC 78	9.1	0.30
	11 DEC 78	23.6	0.40
	12 DEC 78	8.6	0.25
	13 DEC 78	9.4	0.30
Y-UNAIDED	11 DEC 78	11.9	1.1
	12 DEC 78	19.6	0.63
	13 DEC 78	13.1	0.77

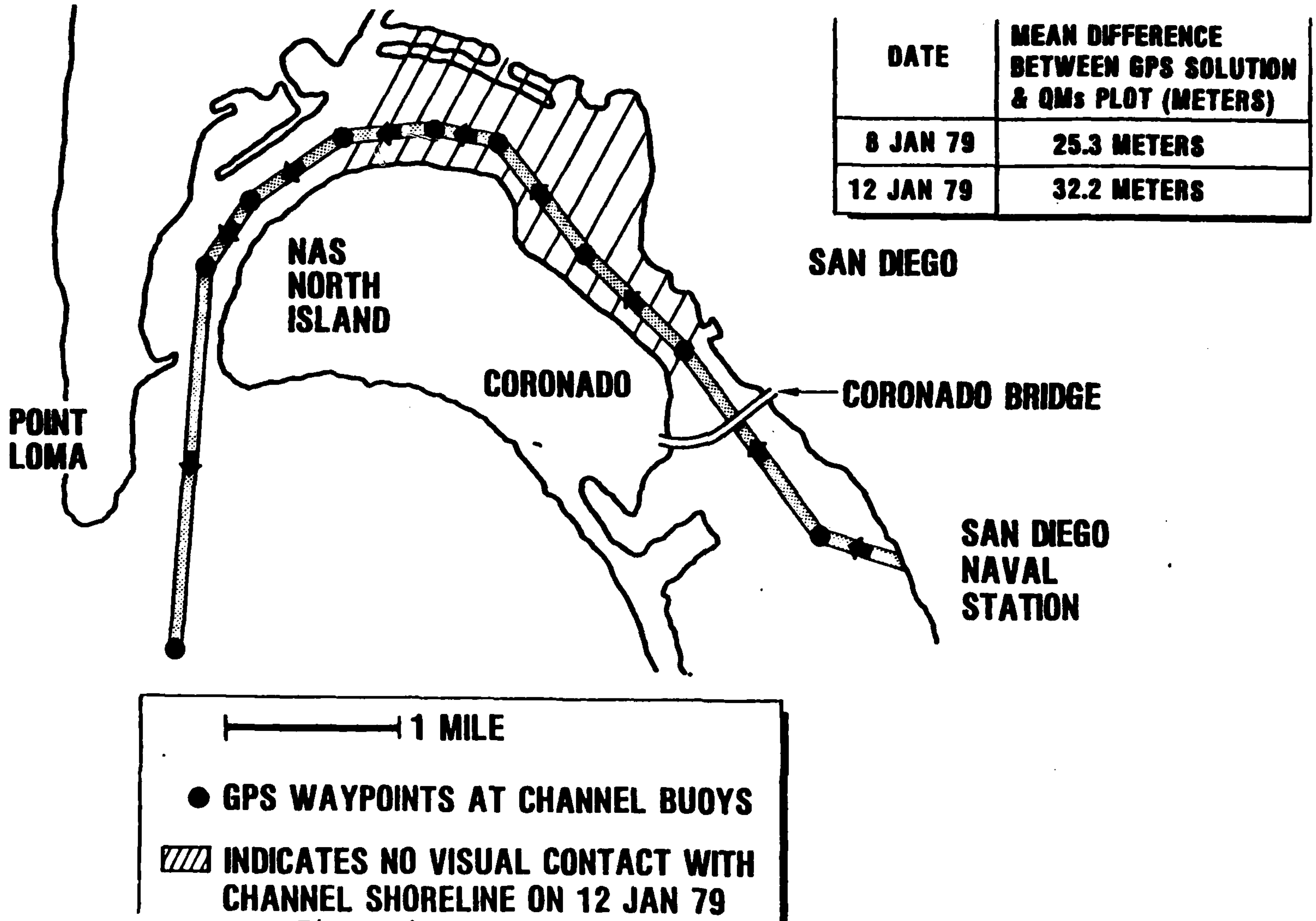
Figure 4-6 Landing Craft Navigation Accuracy Test Summary

(Source: Reference 25, p. 11)

three satellites were clustered above 70^{o} elevation. However this effect was short-lived and will not exist under the 24-satellite constellation envisioned for NAVSTAR. In addition, blind rendezvous between a Navy P-3B Orion aircraft and the LCU were conducted with very satisfying results.

Tests with the USS FANNING were conducted in a number of situations; harbor navigation, naval gunfire support (NGFS), man overbaord recovery, precision anchorage, extended at-sea navigation and radio frequency interference (RFI). User equipment used aboard FANNING permitted entry of 3-dimensional positions into the computer; comparison of these "waypoints" with the current NAVSTAR position enabled the equipment to compute ranges, bearings and times-to-go, not unlike comparing intended track with dead reckoning (DR) positions and actual fixes. No Mini-ranger type system was used aboard the frigate. However, comparisons between NAVSTAR plots and the Quartermaster's visual plot, accurate to 20 meters optimal, were made frequently.

The Harbor Navigation tests were conducted in San Diego channel, between the San Diego Naval Station and Point Loma. For test purposes, the channel buoy positions were used as waypoints and bearing, range and time to turn information were relayed to the Officer of the Deck (OOD) via sound-powered phones. Figure 4-7 depicts the mean difference between visual and NAVSTAR plot. During one run, visual fixes could not be obtained due to poor visibility; as a result, the ship navigated by NAVSTAR only. The Commanding Officer (CO) observed that NAVSTAR positional errors were 10 to 40 yards greater



DATE	MEAN DIFFERENCE BETWEEN GPS SOLUTION & QMs PLOT (METERS)
8 JAN 79	25.3 METERS
12 JAN 79	32.2 METERS

Figure 4-7 Frigate Harbor Navigation Test Results

(Source: Reference 25, p. 15)

than visual fixes, perhaps due to the location of the NAVSTAR pallet on the aft flight deck: further, under reduced visibility conditions, NAVSTAR fixes agreed closely with fixes obtained by radar.[117]

The NGFS test was invalidated due to an error in the gunfire-control system. However, from all appearances it seemed certain that NAVSTAR would prove very valuable in support of the naval gunfire mission. The man overboard test was conducted with and without NAVSTAR input. In the latter case, the ship returned to within 350 yards of the overboard position; in the former, NAVSTAR updates returned the frigate to within 15 yards.[118] The precision anchoring tests showed that the continuous information update provided by NAVSTAR would be of near-invaluable assistance in navigating a vessel to a precise anchorage position. The actual error of 40 yards in one instance, was due to human error regarding information relay and internal organization, and not to any demonstrated error in the NAVSTAR user equipment. A second drill, conducted later using visual fixes as the primary method and NAVSTAR for comparison, showed that NAVSTAR again displayed a 10 to 40 yard error relative to the visual fixes.[119]

The extended at-sea trial took place when FANNING deployed on a 10-day cruise to Acapulco, Mexico. No hard data was provided in the field test report, though it did indicate that

---

[117] Ibid., p. 16.

[118] Ibid., p. 17.

[119] Ibid., p. 20.

there was good agreement between NAVSTAR information and visual/radar fix information. The frigate's Commanding Officer noted that NAVSTAR data was very valuable especially during days when skies were overcast, precluding celestial fixes, or when the ship was too far from land to take visual or radar fixes.[120] He further noted that NAVSTAR proved to be independent of such adverse conditions as weather etc., and GPS continued to provide fix information that was both accurate and timely. Finally, in the RFI tests it was found that a number of various signals received (TACAN, radar, DECCA navigation, TV and FM radio) had no effect on NAVSTAR user equipment operation.[121]

In summary, NAVSTAR Phase I tests validated many assumptions about the concept of using passive ranging satellites for navigation. FANNING reported that NAVSTAR's reliability was exceeded only by visual/radar fixes close in to land and will be superior to all other means of navigation-celestial, OMEGA, LORAN, bottom contour - once full coverage is a reality.[122] These shipboard tests revealed a number of facts which were incorporated into the final conclusions of the Final Field Test Report. Some of these were: NAVSTAR can provide at sea position accuracy of 20 meters or better; GPS can greatly enhance at sea rendezvous and restricted water navigation; NAVSTAR can greatly increase the chances of

---

[120] Ibid.

[121] Ibid.

[122] Ibid., p. 24.

recovering a man overboard and precise anchoring is also much enhanced. The advantages of NAVSTAR for shipboard use becomes readily apparent: all-weather, continuous, global, requiring no special charts while providing such diverse information as time-to-go to an event and steering data to some location.

D. SYSTEM COSTS

The intent of this section is to detail the costs surrounding LORAN, OMEGA and NAVSTAR. There are some problems with this approach. Recent data in many instances is not available. In the case of NAVSTAR, much data has not yet been generated, let alone collected and analyzed. In addition, the source of the data may have biased the information, to some degree, depending on the intentions of the author(s).

The most recent data available on a comparitive basis is depicted in Figure 4-8. It should be noted that the information was collected for the FAA, whose emphasis is toward the aviation community and not the maritime community. However it does provide a sense of the magnitude of funding that will be required for future navigation system requirements. Figure 4-9 provides less-timely cost information (circa 1977) but breaks the costs down to show at what levels civil users in the maritime arena will be financially burdened. Finally, Figure 4-10 breaks down USCG LORAN and OMEGA costs for 1976 and 1977 (LORAN-A included).

A very important cost item yet to be discussed concerns the NAVSTAR C/A mode receiver (Z set) for civil maritime use.

	YEAR	NUMBER	AMOUNT ($ million)
NAVSTAR GPS[1]			
Government System Investment			
1. Research & Development	1990		400
2. Satellites and Control	1990		200
3. Satellites and Control	2000		400
User Equipment Investment			
1. DoD	1990	27,000	810
OMEGA[2]			
Government System Investment			
1. U.S. Owned/Operation Stations	1976	2	20
2. U.S. Investment in non U.S. Stations	1980	6	50
User Equipment Investment			
1. U.S. Maritime	1980	3,000	15
LORAN-C[3]			
Government System Investment			
1. Transmitter Stations	1976	27	153
2. Transmitter Stations Added	1977-80	12	65
User Equipment Investment			
1. Civil Ships/Pleasure Craft	1976	1,000	4
2. Civil Ships/Pleasure Craft	1980	77,000	100

Figure 4-9 Navigation System Costs

(Source: Reference 8)

[1] p. 3-14.
[2] p. 3-6.
[3] p. 3.5.

	30 JUNE 1976	30 SEPTEMBER 1977
LORAN A Stations	$4.54	$ 4.91
LORAN C Stations	9.33	11.17
LORAN A/C Stations	5.02	5.45
LORAN C Monitors	1.40	1.50
OMEGA Stations	3.20	4.48
Other Units	1.34	1.01
TOTAL	$24.83	$28.52

Figure 4-10 Operating Costs for USCG Radionavigation Units (millions of $)

(Source: Reference 26)

One of the issues facing policy makers concerns the number of civil users presently using LORAN-C and those who will begin to use the system shortly. The question arises as to the appropriateness of switching systems in mid-stream, that is from LORAN-C to NAVSTAR, thereby outdating an expensive LORAN receiver and causing the purchase of an equally expensive, or even more costly, NAVSTAR receiver. To address this policy issue one of the first questions to be answered then is how much will a NAVSTAR receiver cost the user? Several industry studies have been completed, along with government-sponsored research, which investigated this matter. Systems Control Inc. (SCI), under contract to FAA, concluded that a low cost NAVSTAR receiver set (C/A mode) would cost approximately $5765.00.[123] This figure was based on the assumption of 240,000 potential civil aircraft users and did not account for potential maritime users of NAVSTAR. GAO, on the other hand, foresees more than 636,000 U.S. users by the 1990's (including over 396,000 maritime users).[124] Studies by ARINC Research Corporation estimated a $3,620.00 cost for a Z-set, while a MITRE Corporation study projected an estimated cost of about $2,800.00 for a civil NAVSTAR receiver.[125] These differences indicate that further analysis should be undertaken. A major element in these studies is the question of available accuracy for the civil user. If

---

[123] Reference 27, p. 17.

[124] Ibid., p. 18.

[125] Ibid., p. 19.

the C/A mode accuracy is not attractive enough to the potential user, there will be no motivation to switch to NAVSTAR from other systems. Therefore, a high-level policy making effort will be required by U.S. government officials before the receiver cost issue can be equitably dealt with. To say at what level this decision must be made is beyond the scope of this paper.

V. THE CIVIL MARITIME INDUSTRY SURVEY

A. INTRODUCTION

During the course of this investigation no references were discovered which made any mention of the civil maritime industry's side of the navigation system issue. It appeared that no effort, widespread or otherwise, had been expended to determine their navigation needs and wants. This is, in part, understandable owing to the federal mandates already in existence (and discussed in Chapter II) which establish the requirements for safe navigation. Unfortunately this remains a substantial oversight once the maritime population is examined in more detail. Figure 5-1 presents figures which depict ship and boat populations in 1973, and 1976, as well as estimated 1990 figures. As estimated population of over 26 million vessels is anticipated by 1990. This represents a vast potential for users of NAVSTAR. Therefore, some consideration for the thoughts and desires of mariners was felt to be in order. It should also be pointed out that some 126,000 commercial vessels were not included in the Coast Guard's survey.[126]

Figure 5-2 presents a closer scrutiny of the potential users of NAVSTAR. It represents an estimated percentage of the total vessel population for the specified year that carry

---

[126] Reference 27, p. 41.

TYPE	1973	1976	1990 (estimates)
Commercial (over 5 tons)	54.4	68.7	126.5
Pleasure:			
Class A (under 16')	5,680	7,000	12,473
Class I (16'-25')	3,550	5,257	12,780
Class II (26'-39')	293	418	1,338
Class III (40' and over)	68	78	132
TOTAL	9,645	12,822	26,849

* Figures in thousands of vessels.
1973, 1976 data obtained from USCG Boating Surveys for respective years.

Figure 5-1 Ship and Boat Population*

(Source: Reference 27, p. 39)

TYPE OF EQUIPMENT	1973 Do Carry	%[2]	1976 Do Carry	%[2]
RDF[3]	163	1.7	294	2.3
Radar[3]	35	.4	114	.9
LORAN-A (automatic)	20	.2	48 ± 18	.4
LORAN-A (manual)	39	1.4	97 ± 26	.8
LORAN-C	3	.03	25 ± 13	.2
LORAN-A/C	1	.01	25 ± 13	.2
OMEGA	26	.3	35 ± 15	.3
TOTAL	287	4	638	5.1

[1] Figures in thousands of vessels.

[2] Percent figures are for that year's total vessels.

[3] RDF, Radar unlikely to be replaced by SATNAV.

NOTE: These figures for U.S. only. Foreign vessels will require further attention.

Figure 5-2 Estimate of Vessels Carrying Electronic Navigation Equipment[1]

(Source: Reference 27, p. 40)

some form of electronic navigation equipment. For example, in Figure 5-1, the total recreational vessel population is 12.75 million vessels. The 1976 total of 638,000 in Figure 5-2 is 5 percent of the 12.75 million population (5 percent is the column total for 1976 percent). The source study generated a 1990 estimate for vessels carrying electronic equipment by deleting RDF and radar from consideration (thereby obtaining a percent value of approximately 1.9) and assuming an error in the LORAN/OMEGA census on the high side. This yielded a revised percentage value of 1.47 for vessels that might carry LORAN, OMEGA or TRANSIT in 1976. By applying this 1.47 figure to the estimated 1990 population, a generated value of 396,000 users of LORAN/OMEGA/TRANSIT was obtained.[127] This figure represents a large number of potential NAVSTAR users and lends further credence to the need for research effort directed at present and future satellite navigation users.

It was this desire to investigate the civil maritime side of the navigation dilemma that prompted the informal non-statistical survey which encompasses the remaining portion of this section. It was never intended to be the ultimate study of the industry's wishes. The sample size was small and the questionnaire was rather generalized.

Its purpose was solely to obtain a feeling of the pulse of civil maritime navigators, to learn what the freighters,

---

[127] Ibid.

tugs and fishermen thought of the navigation systems available today and how they viewed the arrival of satellite navigation (TRANSIT today and NAVSTAR in the near-future).

B. THE SURVEY

The first step in conducting this survey was to generate an assorted list of civil maritime industry members, to include steamship companies, tow and barge firms, fishing organizations, etc. Lieutenant James Garrett, USCG, was of great assistance in providing a number of names and addresses. The final list (See Figure 5-3) used in mailing the surveys was generated through volume 2 of the USCG publication Merchant Vessels of the United States, (CG-408). An entire section details the addresses of managing owners (by combining this index, page by page, a list of companies was obtained). There were few criteria in making selections. If the firm was large and well-known, such as LYKES, it was selected. If it was relatively unknown, it was selected on the basis of having a large number of vessels (boats, barges, etc.) listed beneath the parent name in CG-408. Using these informal criteria, CG-408 yielded 43 various companies. Forty-four companies are listed in Figure 5-3 because one firm in the initial list forwarded a survey to another company which responded as well.

Once the group of firms to be surveyed was selected a contact letter was prepared for each company. Figure 5-4 depicts the form of this letter. Each company received an original typed copy rather than a mimeograph or photocopy

NAME		ADDRESS	RESPONDED
1.	Agri Trans Corp.	Long Grove, IL	Yes
2.	Aiple Towing Co., Inc.	Wilmington, DE	No
3.	Alaska Packers Assoc., Inc.	Blaine, WA	Yes
4.	Allied Towing Corp.	Norfolk, VA	Yes
5.	American Commercial Lines	Houston, TX	No
6.	American President Lines	San Francisco, CA	Yes
7.	Baltimore Towing & Lighterage	Baltimore, MD	Yes
8.	Brown & Root, Inc.	Houston, TX	Yes
9.	Brownsville Shrimp Exchange and Cold Storage	Brownsville, TX	Non-existent
10.	CWC Fisheries, Inc.	Ketchikan, AK	Non-existent
11.	CENAC Towing Co., Inc.	Houma, LA	No
12.	Central Gulf Lines, Inc.	New Orleans, LA	No
13.	Chevron Shipping Co.	San Francisco, CA	Yes
14.	Crowley Maritime Co.	San Francisco, CA	Yes
15.	Delta Lines	Oakland, CA	Yes
16.	Delta Steamship Lines, Inc.	New Orleans, LA	Yes
17.	Dixie Carriers, Inc.	Wilmington, DE	Yes
18.	East Coast Trawling and DK Co.	Leesburg, NJ	No
19.	Elevating Boats, Inc.	Braithwaite, LA	Yes
20.	Exxon Company	New York, NY	Yes
21.	Farrel Lines	San Francisco, CA	No
22.	Fisherman's Packing Corp.	Anacortes, WA	No
23.	Foss Launch and Tug Co.	Seattle, WA	Yes
24.	Hawaiian Tug and Barge Co.	Honolulu, HI	Yes
25.	Hennepin Towing Co.	Minneapolis, MN	Yes
26.	Lykes Brothers Steamship Co.	New Orleans, LA	Yes
27.	Matson Navigation Co.	San Francisco, CA	Yes
28.	Mobil Oil Corp.	New York, NY	Yes
29.	Moore McCormack Lines, Inc.	New York, NY	No
30.	New England Fish Co.	Juneau, AK	Non-existent
31.	North Pacific Fishing Vessel Owners Assn.	Seattle, WA	Yes
32.	Pacific Far East Line	San Francisco, CA	Bankrupt
33.	Peter Pan Seafoods, Inc.	Seattle, WA	No
34.	Prudential Lines	San Francisco, CA	Now Delta Steamship
35.	Puget Sound Tug and Barge	Seattle, WA	Yes
36.	San Diego Trans. Co.	San Francisco, CA	Yes
37.	Sealand	Oakland, CA	Yes
38.	Seatran	Oakland, CA	No
39.	Silver Springs, Inc.	Silver Springs, FL	No
40.	Standard Dredging Corp.	Baltimore, MD	Yes
41.	U.S. Lines	Oakland, CA	Yes
42.	Ward Cove Packing Co.	Seattle, WA	No
43.	Waterman Steamship Corp.	New York, NY	Yes
44.	Whitney Fidalgo Seafoods, Inc.	Seattle, WA	No

Figure 5-3 Maritime Industries Surveyed

SMC 1765
Naval Postgraduate School
Monterey, CA 93940
PH: 408-372-8714

24 July 1979

Dear Sir:

I am writing to request your assistance with some research work I have undertaken at the Naval Postgraduate School.

My subject area is "Satellite Navigation: Pro's and Con's for Civil Maritime Use". Realizing that your firm plays a major role in the civil maritime arena, I hope you will be able to provide any information you might consider to be significant. I have enclosed a questionnaire and franked envelope to ease any inconvenience.

If you feel the questions don't address some facet you think important, I would ask that you add as much information as you feel is appropriate. My telephone number is included above, in the went you'd like to discuss this in more detail.

Thank you very much for your time and attention. I look forward to hearing from you.

Sincerely,

Figure 5-4

version. This was designed to facilitate the initial contact and enhance the credibility of the survey in the eyes of the reader. In addition, the words U.S. Coast Guard or USCG were scrupulously avoided in the text of the letter. The reason for this was to avoid inciting the company's representative reading the survey to some non-normal emotional state over the navigation issue faced by the USCG, such as LORAN-C requirements for certain vessels. In addition, in the hopes of increasing the response rate, a franked, addressed return envelope was included in the survey package mailed to each company on the list.

The most important element of the survey was, of course, the questionnaire. A copy of the form is included in Figure 5-5. As can be seen, the questions are more general in intent and content. Brand names, manufacturers and other specifics were avoided. Rather, questions like approximate cost and ranking of requirements were utilized. The questionnaire sought to gain information on how the various firms navigated at present and how they would like to navigate in the future. Finally, additional space was provided to give the responding firm room to comment on the issue of what type of maritime navigation system the United States should provide, as the primary system, to the civil industry.

Figure 5-6 presents the data compiled from the survey. Of the 44 firms queried, 22 responded with completed surveys. Several answered by letter to indicate that the questionnaire did not relate to their firm's specialty. Of the sub-divisions questioned, the large companies had the highest response rate

NAVSAT Questionnaire

______________________________ (company name)

______________________________ (specialty-tow, fishing, steamship, barge, etc.)

1. What is your primary means of coastal (less than 200nm) navigation? Please specify D - day; N - night

Celestial ________ Radar ________
Loran A ________ Radio Beacon ________
Loran C ________ Omega ________

2. What is your primary means of blue-water (greater than 200nm) navigation? D, N

Celestial ________ Omega ________
Loran C ________ Satellite ________

3. If you use LORAN C, what is the price range of your equipment?

$ 0 - 1000 ________
1000 - 3000 ________
3000 - 10000 ________
10000 or more ________

4. If you have satellite capability now, in what price range is your equipment?

$ 0 - 10000 ________
10000 - 20000 ________
20000 or more ________

5. Please rank the following, in order of preference, for your desires in electronic navigation equipment.

High Accuracy ________ Reliability ________
Repeatability ________ Other ________ (please specify)

6. Would you be willing to trade off less expensive and less accurate LORAN for more expensive, more accurate Satellite Navigation in order to achieve 10-100 meter accuracy at a SAT receiver cost 6 or 7 times greater than LORAN?

Please discuss

Yes ________
No ________
Other ________

7. Would you care to comment on the question of whether or not to make SATNAV the primary NAV system for U.S. civil maritime use?

Figure 5-5

Major Carriers	Coastal Navigation Modes	Ocean Navigation Modes	Trade System Feature	Trade LORAN for Satellite	Desire SATNAV as Primary U.S. System
Am. Pres. Lines	L,R	C,S	Reliability	Yes	LORAN not the answer
Chevron	L,R	C,S	Reliability	No	No
Delta Stmshp	R	C,L	Reliability	No	No comment
Exxon	C,L,R	C,L,S	Reliability	Yes	No
Lykes	L	C	Reliability	Yes	Desires one world-wide system
Matson	L,R	C,L	Reliability	No	Yes, give firm option however
Mobil	C,L,R	C,S	Accuracy	Yes	No comment
Moore McCrmck					
PFEL	Went Bankrupt				
Prudential	Now Delta Steamship Lines				
Sealand	L,R,	S	Reliability	Yes	Yes
Seatrain					
U.S. Lines	L,R,S	C,L,S	Reliability		
Waterman	C,L,R	C,S	Reliability	No	No comment
Tug & Barge					
Agri-Trans	V	R		No	No comment
Aiple Towing					
Allied Towing	L	L	Reliability	No	No too costly
Am. Commcl.					
Baltimore Tow.	L,R	C,L	Reliability	No	No comment
Brown & Root	L		Accuracy	No	No
Cenac Tow.					
Cent. Gulf Lines					

Figure 5-6

Crowley	L,R,S	L,S	Reliability	No	Yes
Dixie	R	L	Accuracy		Wanted more info on subject
Foss	L,R	C,L	Reliability	No	When costs go down
Hawaii Tug	R	C	Reliability	Yes	Yes, use it now
Hennepin	Dis not answer questionnaire; said it did not apply				
Puget Sound Tug	L,R	C,S	Reliability	Yes	Yes
San Diego Trans	L		Accuracy	No	No
Standard Dredge	Uses International Tugs; therefore made no comments				
Fishing					
Alaska Packers	Responded without answering questionnaire				
Brownsville Shrimp					
Fisherman's Pack.					
New England Fist					
NorPac Fish. Assn	L,R	L	Repeatability	No	No
Peter Pan					
Silver Springs					
Ward Cove					
Whitney					
CWC					
Other					
Elevating Boats	DR	DR	Reliability	No	Permit free enterprise to decide
Farrel					
East Coast					
Delta Lines					

Figure 5-6(con't)

NOTE: C - celestial

DR - dead reckoning

L - LORAN

R - radar

S - satellite

V - visual

Figure 5-6 Survey Results

while the fishing-related firms were very poorly represented. This may be explained due to the large amounts of capital presently required to obtain a satellite navigation package. The large organizations can more readily absorb this outlay and may be more willing, as a result, to participate in a venture like TRANSIT or NAVSTAR.

Of the companies completing the survey, 77% utilized LORAN-C for CCZ navigation. However, this figure shifted downward for open ocean navigation; only 45% of the firms used LORAN-C and 41% used TRANSIT. Celestial navigation was the preferred method for the high seas. The most desirable characteristic of a navigation system among the surveyed firms was reliability - 76% indicated their preference for this feature over accuracy and repeatability. A more interesting point discovered was that the majority of the companies stated that they were unwilling to trade LORAN for satellite navigation at the present; however, when it came to indicating whether or not satellite navigation was the primary maritime navigation system, more organizations replied in the affirmative than the negative (36% vice 27%). This seems to support a general conclusion that the civil maritime industry is adopting a "wait and see" attitude with regard to NAVSTAR. Once the system and its costs are set forth there will be many users making the switch. This amplifies the belief that the USCG should further investigate the satellite navigation arena in anticipation of a large number of users within the next two decades and the subsequent adoption of a satellite system as the primary maritime navigation system.

VI. CONCLUSIONS

A. OVERVIEW

This paper has attempted to clarify the navigation system dilemma, as faced by the USCG and the federal government. Systems have been discussed which either fulfill the current federal mandates for safe maritime navigation or apparently have the potential to satisfy these requirements and more. A comparison of these competing systems pointed out several facts. LORAN-C does not provide world-wide coverage and suffers from some system degrading factors. It does, however, offer one-quarter mile position accuracy in the CCZ and it is the designated federal radio-navigation system for maritime CCZ operations in the U.S. OMEGA also suffers from various factors and it does not provide the world-wide coverage or accuracy originally planned for. The very question of OMEGA's long-term existence still remains unanswered and will continue so, more than likely, into the near future. TRANSIT, the first generation of satellite navigation, has proven the concept and offers world-wide coverage with excellent position accuracy. It suffers from such factors as large intervals of time between possible fixes; however, in terms of system parameters, TRANSIT is unmatched relative to the various other operational radio-navigation systems.

In contrast to these is NAVSTAR GPS. It is designed to offer high accuracy, world-wide coverage and continuous

availability. Results of Phase I tests lend great credence to the eventual fulfillment of these promises for greater-than-expected levels. Impediments to these promised levels include policy issues, yet to be addressed, specifying levels of accuracy in the C/A mode, and whether or not GPS will become the primary radio-navigation system for the U.S. if not for the world. Another issue, the cost of the user equipment, will further set the pace for the future of NAVSTAR. It is a question more of economics and less of national policy, yet it weighs just as heavily in the final analysis for deciding the worth of GPS as a civil system. Finally, there is the matter of international relations. Foreign flag vessels operating in U.S. waters must conform to the navigation requirements established by Congress. Whether or not the U.S. should consider the navigation problems of foreign flag vessels should be addressed as well. Further, what of possible competing radio-navigation systems being developed by other nations (or already in existence). Should these be examined or disregarded is another question that might be raised.

The answer to these questions, as well as others not directly addressed, need not be formulated at this moment. Yet the groundwork must be laid for the successful transition of GPS from an engineering concept to an operational entity. Dialogue between DOD and the various civil agencies, participating in or interested in the NAVSTAR concept, must continue to take place. There are inherent difficulties to this type of interaction. At the moment there are no commonly accepted means to equate civil and military radio-navigation

requirements. Without this common framework there can be no comparison of needs and systems. It is strongly believed that such a comparison is an important necessity in the effort to draw up a single U.S. radio-navigation plan, comprehensive in scope, that avoids duplication, lowers government operating costs and provides quality navigation service. A first recommendation then is that Coast Guard efforts should be directed towards the achievement of these commonality criteria, in conjunction with all other participating federal agencies.

One of the central issues facing the USCG in the near-term is the maintenance of the service's creditability as the principal U.S. agency for maritime navigation. There are problems with this image at the present time. The Coast Guard did well for itself with the LORAN-C program as this was the first time that the needs of civil users were at the forefront of planning in a federal agency. However, there are a number of items, still incomplete in the plan's structure, that have shaken the solidarity of the service's image. Charting and calibration remain to be performed and upgraded; user education is sorely lacking; program planning has been deficient at times and user receiver specifications are still being awaited. Much of this appears to stem from the Coast Guard's perception of its maritime navigation responsibilities; which seems to be that of a neutral operator providing good navigation signals that may or may not be utilized by the navigator. Another issue facing the Coast Guard in the foreseeable future is the validity of this role and whether or not the service should expand this neutral role or perhaps

even reduce it further. This appears to be a policy matter that must be settled at the uppermost levels of the Coast Guard's Administration or even further up into the top federal levels. The solution to this question thus is beyond the scope of this investigation. There are some options available to the administrators finally designated to set the policy that are readily apparent in analyzing the issue of satellite navigation and how it pertains to the matter of safe, quality maritime navigation in the U.S.

B. OPTIONS[128]

There seem to arise a number of avenues open to the Federal Government (and the Coast Guard) as it pursues its courses of action, relative to navigation, into the last portion of the 20th century. Due to the scope and wide-ranging nature of future radio-navigation schemes, it is obvious that the Coast Guard will not be able to act independently of any other federal agency. Indeed, a part of any plan of action that will arise will be the requirement for well-coordinated planning and action among the various participating agencies such as DOT and DOD. It is for this reason that the first option is to maintain the status quo, that is take no further action or make no further changes to the existing plans and organizations. This is politically

[128] These options originate in a Draft Issue Paper from USCG Headquarters (G-NAN) dated 2 January 1979.

expedient in that the various agencies are able to maintain their existing power structures with no fear of any great loss of prestige or funds. However, this route does not adequately answer the military/civil compatibility and coordination criticisms presently directed at the various managers of radio-navigation systems.

A second alternative is to direct some Federal Agency, already in existence, to develop, update and coordinate a unified radio-navigation plan for the U.S. Candidates might include DOD, DOT, NASA, Department of Commerce (DOC) or the Maritime Administration (MARAD). The advantage of this approach would be to place responsibility for the navigation needs of the country under one omnipotent central agency. This would of course take place under the potential spectre of conflict of interest. Given the political climate of the 1970's this could prove to be a less than desirable solution. Other conflicts may arise as well, depending on the degree of extra authority granted to the directing agency; that is, whether or not the agency would control system development and operation as well. Depending on the final structure, planning authority and operational responsibility might rest with different agencies.

A third option available is to create a new agency responsible for radio-navigation planning, either in the Federal Government structure or the Executive Officer of the President. Again, this would place all authority and responsibility for development and updating of the U.S. radio navigation plan under a single agent, while leaving system development and

operation with existing organizations. The main advantage of this option is the feature of central planning and coordination from an objective "non-operating" agency (one not involved directly with radio-navigation system development and/or operation). The principal disadvantage lies in the combination of the stigma associated with the creation of another federal agency and the additional resources required for its operation. This course of action is also felt to be less than desirable.

A fourth option has several possible aspects to it but, in essence, would require an increase in the means of formalizing and integrating DOD and DOT efforts in radio-navigation planning. This effort might involve a formal agreement between the two agencies for coordinated action in the development of a national radio-navigation plan; or it might extend to the creation of a separate program office under the joint auspices of both agencies. The main feature of this alternative is the clear-cut recognition of both military and civil requirements that must be considered in any U.S.-wide navigation plan. Such a dialogue between DOD and DOT is likely to insure that this recognition will be upheld. There are shortcomings. In the case of a formalized process (including a memo of understanding) integrating DOD/DOT efforts, continuous review would be necessary in order to insure that national interests are maintained. Whether this could be adequately carried out is doubtful. If a joint program office were developed, this would again broach the subject of another governmental agency, requiring more resources

and creating additional administrative loads.

C. CONCLUSIONS

Regardless of the final option chosen with whatever format seems most suitable, it is apparent that, in the near term, the USCG will be at the forefront of maritime navigation planning and policy in the federal government. Legal mandates dictate this. It is also apparent that NAVSTAR is proving itself to be a viable, multi-faceted navigation system with great application in the civil maritime area. It might not be a wise decision for the Coast Guard to begin immediate plans for the phase out of LORAN-C and OMEGA in anticipation of NAVSTAR's full implementation. However, in the face of all the evidence to date, it would be foolish for the service to disregard the arrival of GPS and be left, in effect, "holding the bag" with outmoded systems. In fact, the Coast Guard is not doing this. The service has access to a NAVSTAR user equipment suite, test data will be analyzed by the USCG and the results examined for potential application to Coast Guard cutters as well as civil mariners.

The Coast Guard is in a unique position within the federal structure. It is clearly an active member of the U.S. Armed Forces, sharing in the responsibility for the defense of the American people. However, it also acts as a federal agency active in the civil sector, implementing regulations and enforcing statutes which are decidedly non-defense oriented. The point to make is that the USCG is involved at both ends of the spectrum of radio-navigation in the U.S. - civilian

as well as military. With this unique status comes the responsibility for insuring that the maritime navigation system(s) of this country adequately supports the needs and requirements of both the defense forces and civilian maritime industry/ recreational boating population of the U.S. Major decisions will have to be made in the next few years and the Coast Guard can not afford to minimize or disregard the significance of these. It will be a costly venture, whether LORAN and OMEGA are phased-out and NAVSTAR implemented, or LORAN/OMEGA is upgraded and maintained. But cost cannot be the only measure of a system. In the final analysis, the safety and well-being of the user, be they military or civilian, must bear equal attention along with the economics of any system.

No particular option or recommendation has been offered as the best solution to the maritime delemma facing the federal government and the USCG. These options have been presented, however, in the hopes that further studies, investigations and sessions will examine these, and others, and will eventually develop the "best" system for this country. The one conclusion to be derived from this study is that much more work remains and system developers must further test their concepts; future operator agencies must ready themselves now, and policy makers must address numerous issues and arrive at workable, viable plans which are in the best interests of all.

ACKNOWLEDGEMENT

The materials and assistance proferred by Commander Robert Fenton, USCG and Major R. Jordan, Canadian Armed Forces are gratefully acknowledged. Their research provided a wealth of information that facilitated efforts toward completing this paper.

In addition, Professor Donald Stentz's guidance is most appreciated.

LIST OF REFERENCES

1. General Accounting Office Report LCD-77-109, Navigation Planning: Need For A New Direction, March 21, 1978.

2. Code of Federal Regulations (CFR), Title 33, Navigation and Navigable Waters, revised July 1, 1978.

3. Bowditch, Nathaniel, American Practical Navigator, U.S.N. Oceanographic Office, 1966.

4. Dunlap, G. D., and Shufeldt, H. H., Dutton's Navigation and Piloting, United States Naval Institute, 1969.

5. Strobridge, Truman R., Chronology of Aids To Navigation and the Old Lighthouse Service 1716-1939 (CG-458), U.S. Coast Guard, 1974.

6. Putnam, George R., Lighthouses and Lightships of the United States, Houghton-Miflin, 1933.

7. Weiss, George, The Lighthouse Service: Its History, Activities and Organization, Johns Hopkins Press, 1926.

8. Department of Transportation Report DOT-TST-78-4, National Plan for Navigation, November 1977.

9. Hefley, Gifford, Development of LORAN-C Navigation and Timing, Institute for Basic Standards, 1972.

10. Jansky and Bailey, The LORAN-C System of Navigation, 1962.

11. USCG LORAN-C Operations Manual (CG-222), United States Coast Guard.

12. LORAN-C User Handbook (CG-462), United States Coast Guard.

13. Scull, David C., OMEGA Navigation, U.S. Naval Oceanographic Office, 1971.

14. Watt, J., "The OMEGA System", Navigation Systems, G. E. Beck, ed., VanNostrand Reinhold, 1971.

15. Fenton, R. E., "Coast Guard Navigation Plans", USCG Engineer's Digest, Winter 1979.

16. Magnavox Advanced Products Division Report R-5933, The TRANSIT Navigation Satellite System, by T. A. Stansell, October 1978.

17. Interview with Major R. Jordan, Canadian Armed Forced, USAF Space and Missile Systems Organization, 14 August 1979.

18. Black, H. D., Jenkins, R. R., Pryor, L. L., The TRANSIT System, Johns Hopkins University, 1975.

19. Easton, R. L., "The Navigation Technology Program", NAVIGATION, Institute of Navigation, Summer 1978.

20. Fenton, R. E., Draft Memorandum on NAVSTARGPS, for USCG Headquarters (G-WAN), Spring 1979.

21. Milliken, R. J. and Zoller, C. J., "Principle of Operation of NAVSTAR and System Characteristics", NAVIGATION, Institute of Navigation, Summer 1978.

22. Stansell, T. A., "Civil Maritime Applications of the Global Positioning System", NAVIGATION, Institute of Navigation, Summer 1978.

23. NAVSTAR GPS, Results of Joint Service Field Tests, Phase I Concept Validation, Developmental Test and Evaluation (15 March 1977-5 June 1979), NAVSTAR GPS Joint Program Office, SAMSO, Summer 1978.

24. Magnavox Report (MX-TM-3237-77) presented at ELECTRO77 Proceedings, NAVSTAR GPS User Applications, by Edwin H. Martin, May 6, 1977.

25. Final Field Test Report, Major Field Test Objective Number 12, Shipboard Operations, SAMSO, June 1979.

26. Executive Summary, Operating Costs for Radionavigation Units, USCG Headquarters (G-WAN), 1977.

27. General Accounting Office Report LCD-79-104, Should NAVSTAR Be Used For Civil Navigation?, April 30, 1979.

28. General Accounting Office Report PSAD-79-16, The NAVSTAR Global Positioning System-A Program With Many Uncertainties, January 17, 1979.

29. Department of Transportation Report DOT-TSC-RSPA-78-22, FAA Navigation Program, by Neal A. Blake, presented at the Conference on Navigation in Transportation, Cambridge, Massachusetts, September 19-21, 1978.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 54Js Department of Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
4.	Assoc. Professor D. A. Stentz, Code 62Sz Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
5.	Lieutenant Commander Robert G. Nickerson, USN Code 54No Department of Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
6.	COMMANDANT (G-PTE-1/72) U. S. Coast Guard Washington, D.C. 20590	2
7.	Lieutenant Richard S. Hartman, Jr., USCG CCGD3 (OC) Governor's Island, N.Y. 10004	1
8.	Commander R. E. Fenton, USCG U. S. Coast Guard Headquarters (G-WAN) Washington, D.C. 20590	1